MSc Dissertation Thesis

MSc in Sustainable Energy Systems

Modelling and Cost Analysis of a Hybrid Wind Turbine and Water Tower System as a Means of Energy Storage

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Modelling, Control and Techno-Economic Assessment of a Multi-MW Composite Hybrid Wind Turbine and Water Tower as a Means of Energy Storage

Mission Statement

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Supervisor: Dr. Aristides Kiprakis

Summary and initial literature review

Electricity plays a key role in modern society. The current expansion of renewable energy supply systems, grounded in climate change concerns, has been led by wind energy projects, which are subject to variability of its output due to variations of the wind resource. To help stabilize the generation output of wind projects, energy storage solutions have been proposed and assessed for operation along with wind turbines.

One of the proposed storage systems integrates wind generation with pumped hydro storage, storing water when excess generation is available and depleting the reservoir on excess demand situations. This type of system has been proposed and studied by various papers, from large scale applications [1] to islands and isolated systems operation [2, 3], with one plant already operational in Canary Islands [4]. Optimization algorithms have been proposed and simulated for the operation of these systems [5, 6]. A further development of this type of system uses the wind turbine tower itself as part of the upper reservoir, similar to the project being installed in Germany [7] and described by its US patent [8].

The proposed project focuses on developing a Simulink model of a Multi-MW, grid connected, Hybrid Wind-Hydro generation system, integrated with pumped water storage. The turbine tower will be used as part of the upper reservoir for the system. The software model will allow simulations of the performance of the system with different layouts and the sensitivity analysis of different configurations. A techno-economic assessment of the system will be undertaken to address the viability of the proposed system.

Main aims and objectives

- Create a software model of a hybrid wind-hydro generation system, connected to a three-phase grid, integrated with a pumped water energy storage system within the turbine;
- Assess different alternatives for the components of the system;
- Develop a preliminary control strategy for the system;
- Simulate the system in different scenarios of operation conditions, including:
  - Storing water on excess generation situations;
  - Depleting the reservoir to increase generation in excess demand situations;
  - Holding a constant generation output for as much time as possible.
- Undertake a sensibility analysis of performance and techno-economic viability of the system.

Interim targets

Familiarise with MATLAB/Simulink interface and commands; Undertake a literature review of pumped hydro generation and hybrid wind-hydro systems; Research existing models of similar generation systems on Simulink; Create the proposed system on Simulink; Simulation and sensitivity analysis of different scenarios; Assess the Techno-Economic viability of the proposed system; Critical analysis of results; Dissertation writing and poster design.

Methodology and draft work plan

21/02/17 – 21/04/17: Literature review and familiarisation with Simulink;
22/04/17 – 30/04/17: Initial wind and hydro plant models research and familiarisation;
02/05/17 – 22/05/17: Second semester exams;
23/05/17 – 15/06/17: Model development;
16/06/17 – 30/06/17: Model simulation and sensitivity analysis;
01/07/17 – 15/07/17: Techno-Economic assessment and critical analysis of the results;
16/07/17 – 14/08/17: Dissertation write-up and revision.
15/08/17 – 18/08/17: Poster designing and revision;

Required resources

If any resources are required for the project, they will be discussed with the supervisor. A possibility is a field trip to visit to the operational hybrid wind-hydro power plant in Canary Islands.

Health and safety implications

(a) For the proposed project:

- Prolonged use of computers;
- Ergometry.

(b) For the project outcomes (software model):

- Prolonged use of computers;
- Ergometry.

References

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[7] Grumet, T., 2016, *This Unique Combo Of Wind And Hydro Power Could Revolutionize Renewable Energy*. [online], Accessed 18/04/2017; Available from: http://www.gereports.com/unique-combo-wind-hydro-power-revolutionize-renewable-energy/.

[8] Garces, L.J., Y. Liu, and S. Bose, 2007, *System and method for integrating wind and hydroelectric generation and pumped hydro energy storage systems.* Patent No: US 7239035 B2.

Declaration

The supervisor and the student are satisfied that this project is suitable for performance and assessment in accordance with the guidelines set out in the course documentation.

Signed:

William Bellinazo Roca

Dr. Aristides Kiprakis

William Bellinazo Roca

Date: 21/04/2017

Abstract

This study presents the software modelling of a hybrid power plant, integrating wind energy and pumped hydroelectric energy storage and compromising the wind turbine tower as the upper reservoir of the pumped storage scheme, along with a brief cost analysis of the technology. The model is created using *Simulink*, being constituted by four 2 MW wind turbines, a 4 MW hydroelectric scheme and 4 MW pumps. The upper reservoir holds 24,630 m^3 of water and 11 MWh of energy storage. Statistical analysis from real wind data from North Harris, UK, allows the pumped storage scheme to be designed to balance the wind generation output fluctuations, targeting to provide a constant design power output of 4 MW to the grid, equivalent to 50% of the wind capacity installed. Three cases are analysed and compared on the simulations with wind data from North Harris and the cost analysis: wind farm without energy storage, with energy storage inside the turbine tower and with an artificial external reservoir. Results indicate that the storage inside the tower is more expensive than excavating an artificial reservoir of similar storage capacity, as the increased penstock length and tower costs make the alternative more expensive. The total costs for the tower storage and artificial reservoir are 1.83 and 1.60 times higher than the costs for the wind farm without energy storage. The simulation results show that it is possible for the pumped storage scheme to balance the wind output. However, even though a power output within 0.8-1.2 pu of the design power is achieved during 98% of the time in the first 10 hours of simulation, the governor has difficulties balancing the short-term wind variations and variable speed technology would provide a better dynamic response for the system. Furthermore, the reservoir is completely emptied towards the end of the 12-hour simulation, due to a prolonged period of low wind speeds. Therefore, the studied storage capacity is insufficient for providing more than an hourly balance to the power output. Additionally, increasing the tower diameter is suggested as a better alternative for increasing the storage, rather than higher inside the tower due to water pressure issues.

Declaration of Originality

I declare that this thesis is my original work, except where stated otherwise. This thesis has never been submitted for any degree or examination to any other University**.**

William Bellinazo Roca

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List of Symbols

Symbol	Description	Unit
$\boldsymbol{a}$	Mathematical regression coefficient	-
$\boldsymbol{A}$	Area	m^2
$\boldsymbol{c}$	Scale parameter for the Weibull distribution	-
$\boldsymbol{Cp}$	Power coefficient	-
$\boldsymbol{CF}$	Capacity Factor	-
$\boldsymbol{d}$	Diameter	m
$\boldsymbol{E_w}$	Energy produced by a wind farm	J
$\boldsymbol{f}$	Frequency	Hz
$\boldsymbol{F}$	Fraction of time which a particular wind speed is exceeded	-
$\boldsymbol{h}$	Height	m
$\boldsymbol{h_s}$	Reservoir height	m
$\boldsymbol{H_L}$	Head losses	m
$\boldsymbol{H_N}$	Net Head	m
$\boldsymbol{k}$	Shape parameter for the Weibull distribution	-
$\boldsymbol{K}$	Turbulent pipe losses coefficient	-
$\boldsymbol{L}$	Penstock length	m
$\boldsymbol{N}$	Rotational speed	min^{-1}
$\boldsymbol{N_S}$	Specific speed	$kW^{0.5}/(m^{1.25}min)$
$\boldsymbol{J}$	Rotational inertia	$kg.m^2$
$\boldsymbol{N_P}$	Number of pole pairs	-
$\boldsymbol{\bar{P}}$	Average power	W
$\boldsymbol{P_{dump}}$	Power consumption of the dump load	W
$\boldsymbol{P_{ele,hydro}}$	Electrical power output of a hydroelectric scheme	W
$\boldsymbol{P_{ele,pump}}$	Pump electrical consumption	W
$\boldsymbol{P_{ele,wind}}$	Electrical power output of the wind farm	W
$\boldsymbol{P_N}$	Nominal Power	W
$\boldsymbol{P_W}$	Power at the rotor of a wind turbine	W
$\boldsymbol{Q}$	Volumetric flow rate	m^3/s
$\boldsymbol{R}$	Radius	m
$\boldsymbol{t}$	Time	s
$\boldsymbol{T_E}$	Electrical torque, as seen by the generator	N.m
$\boldsymbol{T_R}$	Rotor torque	N.m
$\boldsymbol{U}$	Wind speed	m/s

$\overline{U}$	Mean wind speed	m/s
$\overline{U}_{water}$	Mean water speed	m/s
V	Volume	m^3
W	Cost	£
x	Mathematical regression variable	-
Y	Specific work	m^2/s^2
z_o	Surface roughness	m
η_g	Efficiency of the hydro generator	-
η_m	Efficiency of the pump motor	-
η_{pump}	Efficiency of the pump	-
η_{RT}	Round trip efficiency	-
η_t	Efficiency of the hydro turbine	-
λ	Tip-Speed Ratio	-
μ	Dynamic Viscosity	Pa.s
ϕ	Friction factor	-
ω	Angular velocity	rad/s

Glossary

AC	Alternating Current
AAEY	Average Annual Energy Yield
CAES	Compressed Air Energy Storage
CFD	Computational Fluid Dynamics
DC	Direct Current
DFIG	Doubly Fed Induction Generator
FES	Flywheel Energy Storage
GHG	Greenhouse Gases
HAWT	Horizontal Axis Wind Turbine
HDPE	High Density Polyethylene
LTES	Latent Heat Thermal Energy Storage
ORES	Ocean Renewable Energy Storage
PHES	Pumped Hydroelectric Energy Storage
PMSG	Permanent Magnet Synchronous Generators
pu	Per Unit
PWM	Pulse Width Modulation
rad	Radians
RPM	Revolutions per Minute
SDR	Standard Dimensional Ratio
SMES	Superconducting Magnetic Energy Storage
STES	Sensible Heat Thermal Energy Storage
UK	United Kingdom
VLH	Very Low Head Hydropower

1. Introduction

1.1. Motivations

Electricity plays a key role in modern society, shaping day-to-day life as humanity knows it today. Its supply is an engineering challenge, requiring technical expertise and integration of multiple fields, along with an assessment of environmental, safety and socio-economic aspects.

Currently, concerns about global climate change consequences and the unsustainable use of limited resources have motivated an expansion of renewable energy systems. Wind energy has been one of the leaders of the recent renewables development, as the installed wind power capacity in the world increased from around 17 GW in 2000 to 433 GW by the end of 2015 [1, 2]. In addition, wind energy is projected to continue growing, as [3] presents targets of 1,400-1,600 GW by 2030 and 2,300-2,700 GW by 2050.

However, despite the necessity of decarbonization of the global energy supply, energy sources like wind or solar energy are known to have an intermittent output due to their dependency on natural resources. This characteristic results in fluctuations of the electricity output from each wind turbine, which compromise the reliability of wind energy as the grid requires stable power generation to balance the frequency.

Energy storage systems have been suggested to smooth the output of wind farms and reduce periods without energy supply [4, 5]. Many benefits are associated with energy storage, including energy management, power quality improvement and shaving peak daily loads [6, 7]. Integration with wind farms is also suggested to increase the security of energy supply and allow higher wind energy penetration on a country's energy mix [5, 8].

Pumped hydroelectric energy storage is the leader of large scale energy storage projects, with 99% of the total energy storage installed capacity [9]. Although integration of wind with PHES systems has been proposed by several studies [10-12], few projects have been tested on large scale, with only one plant operational in Canary Islands [13]. Considerable investments with energy storage systems and risks associated with a new technology could be halting further interest and investments in energy storage [14].

Since large scale electricity generation projects require high capital expenditures to be implemented, software modelling allows a cheaper and easier assessment of a technology. Computer models are a representation of reality, which allow engineers and researchers to study a particular problem prior to implementation or for research purposes, with a reasonable level of precision.

This thesis focuses on developing a *Simulink* model of a Multi-MW, grid connected, hybrid wind energy and pumped hydroelectric energy storage system. The wind turbine towers are used as the upper reservoir, as the hydroelectric system will aim to balance the power output of the wind farm. This particular scheme is similar to the project currently being installed in Germany, which incorporates the base of the turbines as part of the upper reservoir [15]. The *Simulink* model is set to be tested with real wind data from a real site in the UK to verify its performance. Additionally, this study presents a brief cost analysis of the system, which is presented to provide insights about the economic feasibility of the scheme.

1.2. Scope and Project Objectives

The scope of the project is to deliver a working *Simulink* model of a hybrid wind-hydro power plant, integrated with a pumped storage system which compromises the tower of each turbine as the upper reservoir for the scheme.

The project aims to address the following topics:

- Conduct a literature review of hybrid wind-pumped hydroelectric storage systems;
- Create a software model of a hybrid wind energy and pumped hydro storage system, integrating water storage within the turbine and connected to the electrical grid;
- Develop a preliminary supervisory control strategy for the system;
- Simulate the model with real wind speed data and compare the system with different design case studies;
- Analyse the performance of the scheme and preliminary costs of the system;
- Provide insights about the techno-economic feasibility of the water storage inside the tower as a reservoir for PHES schemes.

1.3. Document Structure

This thesis is divided into 5 chapters and contains 9 different appendices.

Following the introduction on this first chapter, Chapter 2 displays a brief background of wind energy, pumped hydroelectric energy storage, hybrid wind-pumped hydroelectric storage systems and software modelling of hybrid energy generation and energy storage systems, while reviewing relevant publications and projects.

Chapter 3 presents the methodology used in this study. The assumptions and boundaries of the analysis are listed in the beginning of the chapter. Afterwards, a description of the system purpose and characteristics is presented, stating all design considerations and calculations involved. Subsequently, the *Simulink* modelling is described, presenting the starting point for the models, the alterations required and the final model produced for the simulations.

In Chapter 4, the results of the simulation for the design case studies are laid out. The analysis is divided into the short-term results, with 5-minute simulations, and 12-hour simulation results. The cost analysis is also presented, with an estimation of the total costs for all cases analysed. A discussion and comparison of the performance and cost of each case studied is also presented.

Lastly, the summary of the dissertation and the main conclusions from this study are displayed in Chapter 5. Recommendations for future projects, on related topics that could not be detailed due to time constraints, are also presented.

2. Background and Literature Review

2.1. Introduction

In this chapter, the background to wind energy, pumped hydroelectric energy storage and software modelling of renewable energy is provided. The main physical principles and equations for the energy conversion of wind and water potential sources are presented, along with details about the electromechanical topologies available for these sources. These are laid out to provide insights and justify the design choices of the project for both the simulations and the techno-economic assessment. Additionally, a literature review of related studies, the state-of-art and current technologies are provided for the discussed topics.

2.2. Wind Energy

2.2.1. Wind Resource

Wind is an abundant, clean and free source of energy. Global winds at high altitudes are primarily originated by pressure gradients between air masses, which are described by [16] as a consequence of the "uneven heating of the earth by solar radiation" and Coriolis effect due to the earth's rotation.

On lower altitudes, the earth's boundary layer adds complexity to the flow patterns, as wind velocity is zero immediately near the surface and the mean speed increases with an approximately logarithmic profile until reaching geostrophic wind speed at higher altitudes [17]. Furthermore, local characteristics such as surface roughness, orography, obstacles and turbulence affect winds, resulting in a significant variance of wind speed and direction geographically and temporally.

Although wind speed and direction are difficult to predict at specific instants, average values through time allow visualization of trends in wind data for a site, which are used for wind energy assessment purposes. For electricity generation purposes, measurements onsite are carried to determine the average wind direction and particularly the average wind speed, which has a significant impact on energy production and consequently on wind projects' revenue. These measurements are normally performed by anemometric towers, with alternatives being remote sensing measurements with SODAR and LIDAR [18].

To estimate the wind speed at different heights than originally measured, the power law or logarithmic law can be used. The logarithmic law is described by Equation 2.1, adapted from [17].

$$U(h_1) = U(h_2)\frac{\ln\left(\frac{h_1}{z_0}\right)}{\ln\left(\frac{h_2}{z_0}\right)} \qquad \text{(Eq. 2.1)}$$

Statistical analysis provides averages and confidence intervals for wind data. Using probability density functions, like the Weibull or Rayleigh distributions, allows an estimate of the probability of occurrence of each wind speed at a site at any moment. The Weibull distribution is described by Equation 2.2, adapted from [19]. The Rayleigh distribution is a particular case of the Weibull distribution, being the parameters $k = 2$ and $c = 1.13\bar{U}$ [19]. With this data and the power curve of a selected wind turbine, an estimate of the average power and the average energy production of the turbine can be found [16].

$$F(U) = e^{-\left(\frac{U}{c}\right)^k} \qquad \text{(Eq. 2.2)}$$

The results of this analysis allow a reasonable estimate of the energy production at that site and are the base data for techno-economic assessment of wind energy projects. Further analysis may be carried on micro-siting of the turbines, which will select the most appropriate placement for turbines on a site and may involve specific software and CFD analysis for complex terrains [20].

2.2.2. Wind Energy Generation

To produce electricity from the wind resource, a wind turbine is used. These machines extract kinetic energy from the wind, converting it to mechanical energy on the rotor of the turbine and later to electricity with an electromagnetic generator.

Wind energy generation is renewable, doesn't produce gas emissions or consume fuels on generation phase. As per 2014, wind energy supplied about 2.74% of the global electricity demands, with a projection of reaching 15-18% by 2050 [2, 3]. In addition, more than 1 million jobs were associated with wind energy in 2015 [21].

Wind and other intermittent renewables are dispatched with priority on energy markets, usually displacing fossil fuel generation, preventing GHG emissions and lowering the price of spot markets due to low marginal generation cost [22, 23]. Wind power plants also do not require water consumption, as opposed to conventional power plants [24]. However, some environmental problems can be associated with wind power, including noise, electromagnetic interference, radar interference, visual impact and impact on wildlife [24, 25].

The "most common design of wind turbines" use horizontal axis, being 3 blades HAWT used in the majority of projects to date [16]. The vectorial sum of the incident atmospheric wind and the tangential wind (produced by the passing rotor blade) create a resultant wind speed, which originates the forces of lift and drag throughout each blade. The lift component parallel to the rotor plane is useful for power production, favouring the rotation of the blades, while the component perpendicular to the rotor plane causes structural efforts on the blades. The mechanical power on the rotor of a HAWT is given by Equation 2.3, adapted from [16].

$$P_W = \frac{1}{2}\rho A U^3 Cp \qquad \text{(Eq. 2.3)}$$

The largest installed wind turbine up to date has a 6 MW nominal power rating with a rotor diameter of 126 m [22]. The maximum power coefficient achievable for a wind turbine is equivalent to approximately 59.3% of the available wind power, which is known as the Lanchester-Betz limit [19, 26]. Modern wind turbines can achieve a power coefficient up to 50%, depending on their design [16].

The main components of a wind turbine are shown in Figure 2.1. The rotor is connected to a shaft and to a generator to convert the mechanical energy input into an electricity output. Alternative configurations for the electromechanical conversion components, which can include a gearbox and different types of generator, are detailed in Section 2.2.3. All electromechanical components of the wind turbine are normally enclosed in the nacelle and the rotor hub.

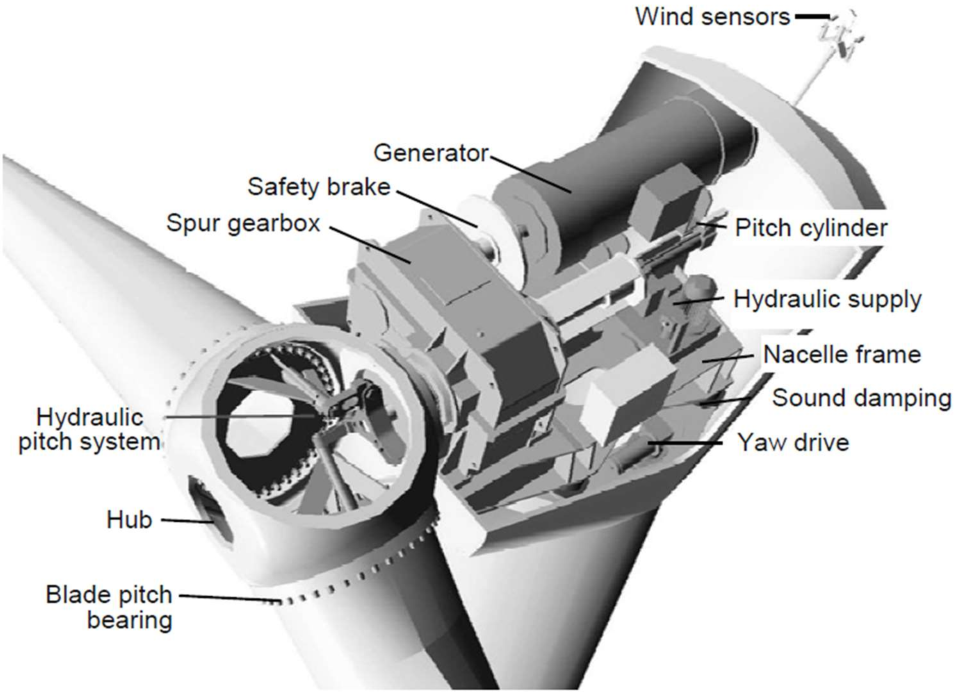

Figure 2.1 – Main components of a wind turbine [17].

Modern turbines operation with variable pitch allows increasing the pitch angle of the turbine blades to limit power at high wind speeds, while also improving the start-up sequence and the power control [17]. Individual pitch angle adjustment per blade was introduced to reduce the loads on blades [27]. The yaw system also adjusts the turbine alignment according to the incident wind direction, normally measured on the nacelle along with wind speed.

Rotor blades can be made of glass or carbon fibre composite materials, wood or steel, depending on structural requirements and costs [19]. They are usually twisted along the blade length and have variable chord length to account for the variable tip-speed ratio along the blade, described by Equation 2.4, from [19].

$$\lambda = \frac{\omega R}{U} \qquad (\text{Eq. } 2.4)$$

The tower, which supports the nacelle and elevates the turbine up to the desired hub height, is normally made out of steel or concrete for onshore projects [16]. Foundations, usually made of concrete and steel, are placed underneath the tower to keep the tower upright and resist extreme loads and overturning moment conditions, with different design types available [16, 19].

Costs for wind energy projects tend to vary with the location and type of technology. [22] provides a range of 1000-1350 €/kW (900-1200 £/kW, with an exchange rate of 1 £ = 1.11 € [28]) installed for projects onshore in Europe and 2000-2200 €/kW (1800-2000 £/kW) installed offshore.

2.2.3. Types of Generator and Grid Connection

Different topologies are available for electromechanical conversion and grid connection of a modern wind turbine. Electrical generators operate as regenerative brakes, removing energy from a prime-mover and converting it into electricity, which appears as a consequence of the interaction between the rotating magnetic fields of rotor and stator [29]. Gearboxes are normally required to connect the rotor and the generator, as the former rotates at a much lower speed than required by the generators.

The equation of motion for a wind turbine, adapted from [16], is presented in Equation 2.5.

$$T_R + T_E = J\frac{d\omega}{dt} \qquad (\text{Eq. } 2.5)$$

Early designs for the generator of wind turbines used fixed speed operation. In these machines, the generator is directly connected to the grid, which fixates the operational speed of the generator, and the rotor consequently. This mode of operation is not ideal since wind turbines achieve optimum electrical conversion (maximum power coefficient) on a certain tip-speed ratio, which varies according to wind speed.

Modern wind turbines allow variable speed operation, which uses power electronics to modulate the power output to match the grid requirements and allow the rotor to operate within a certain range of speeds, as detailed by [30]. This enables tracking the maximum power coefficient in low or medium wind speeds, maximizing the output according to the optimal tip-speed ratio, and allows for correction of electrical power quality, such as power factor correction. Both main types of variable speed generators, synchronous and DFIG, are detailed in the next sub-sections. Generally, wind turbines are sold complete, limiting the choice of a different generator for example, but characteristics of a particular generator may be attractive to specific or custom projects.

Large scale wind turbines normally have a transformer in the nacelle, elevating the voltage to medium voltage levels and reducing the current [19]. Electrical and control cables are normally extended inside the wind turbine tower, from the nacelle to the ground level connection point. At ground level, a common bus connects all turbines to the wind farm substation, which elevates the voltage to the required grid voltage and compromises protection and measurement instruments.

Grid stability studies must be carried before connecting a wind power plant to the grid, including fault analysis, voltage regulations, harmonics, etc. However, power quality and stability is outside of the scope of this particular study and will not be detailed.

2.2.3.1. Synchronous Generator with Full-Rated Converter

In a synchronous machine, both rotor and stator magnetic fields rotate at synchronous speed, defined by Equation 2.6, adapted from [29].

$$\omega_S = \frac{2\pi f}{N_P} \qquad \text{(Eq. 2.6)}$$

Synchronous machines can have either rotor windings, which are supplied with a DC field current, or permanents magnets to create the rotor magnetic field. For a generator, the rotor magnetic field leads the stator field and vice-versa for a motor.

The wind turbine with a synchronous machine and variable speed configuration uses full-rated AC-DC-AC converters for grid connection. Figure 2.2 exemplifies the configuration with a full-rated converter.

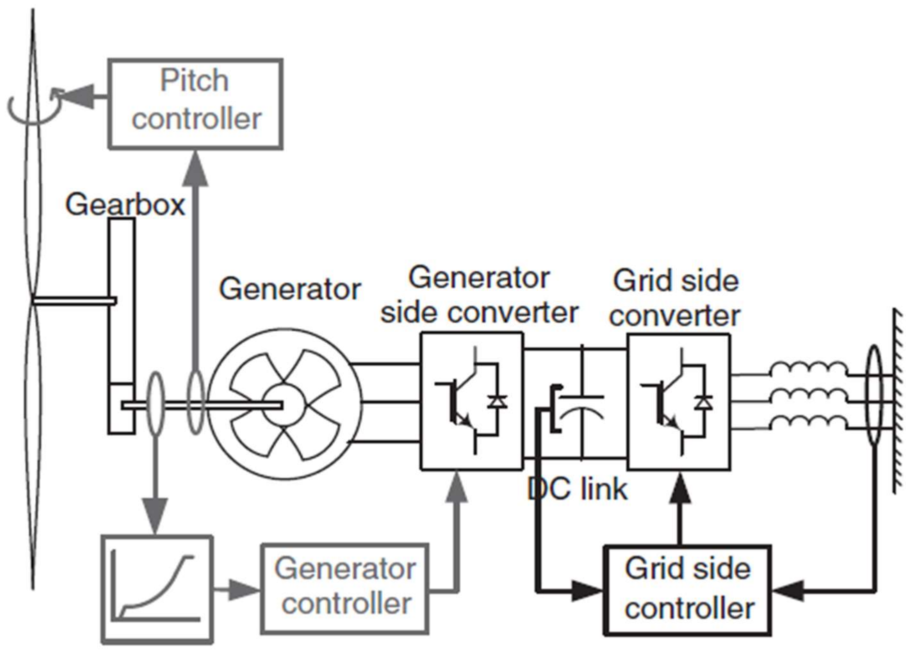

Figure 2.2 – Configuration of a wind turbine with a full-rated converter [19, 31].

As shown in Figure 2.2, all electricity produced passes through the converters, which are controlled to match the grid requirements. Different configurations can be used for the power electronics, as detailed by [32]. When two back-to-back PWM converters are used, the generator side converter allows tracking of the maximum power coefficient for the wind turbine, while the grid side converter keeps the DC link voltage constant and adjusts the output signal.

One of the advantages of the synchronous machine is that it has a higher AAEY than the DFIG, but it is more expensive and heavier in comparison [33]. PMSG have the advantage of not requiring external DC excitation, but their applications can be limited on large scale designs, as large volumes of permanent magnets are required and it is a rare and expensive material [19, 32]. These machines can have either a radial or axial flux design. The wound rotor synchronous machine uses part of the rectified electricity as excitation for the rotor and allows control of active and reactive power independently [32].

Recently, some wind turbines eliminated the gearbox, using a synchronous machine with a high number of poles [19]. Such technology is known as direct-drive wind turbines, which enabled the nacelle to be shorter, eliminated the most mechanically complex component of the machine and eliminated excitation losses [33]. This configuration is still more expensive and heavier than the DFIG configuration, even though the best generator alternative is still debatable, as the average annual energy yield for synchronous machines is greater compared to the DFIG [33, 34].

2.2.3.2. Doubly-Fed Induction Generator

The DFIG is composed by a rotor-wound induction machine. For an induction machine, the rotor speed has to be different than the synchronous speed to generate torque. Slip, defined in Equation 2.7, which is adapted from [29], expresses the difference between the rotor speed and synchronous speed as a percentage of the synchronous speed, being negative for a generator and positive for a motor.

$$s = \frac{\omega_s - \omega_R}{\omega_s} \qquad \text{(Eq. 2.7)}$$

For a DFIG, the rotor windings are connected to the stator with solid-state converters, which allow variation of the rotor speed by controlling the rotor AC current. Figure 2.3 displays the DFIG configuration on a wind turbine.

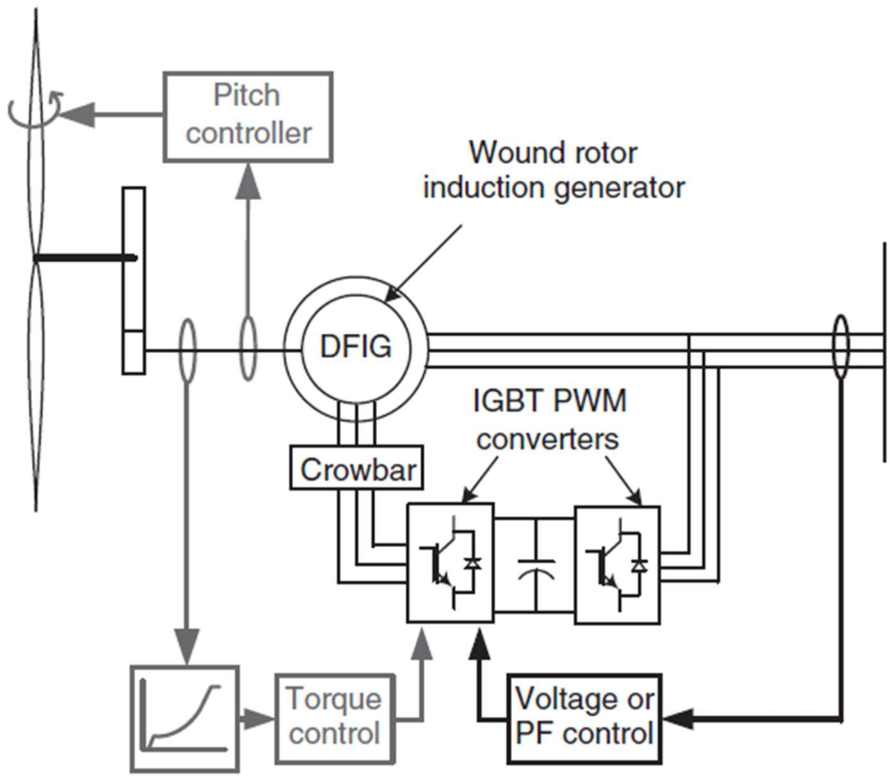

Figure 2.3 – Configuration of a wind turbine with a DFIG [19, 31].

The speed of rotation is controlled by the rotor side converter, which enables tracking the optimum speed and tip-speed ratio to extract maximum power from the wind. The grid side converter controls the power factor and maintains the DC voltage level [31]. Depending if the machine is operating below or over the synchronous speed, part of the total power flows from the grid to the rotor or from the rotor to the grid.

The advantage of the DFIG is that the converter is not rated for the full capacity of the generator, only a small fraction of the produced power needs to go through the converter, generally 25-30% of the generator rated power [30, 32]. Compared to the synchronous generators, the DFIG is cheaper and is more commonly used in current variable-speed turbines [30, 32, 33].

2.2.4. Integration with Energy Storage Systems

Wind generation may have prolonged periods with low wind speed and low energy production. On the other extreme, wind farms may be required to reduce their output or even shut down operation when generation surpasses the demand, due to concerns about the grid stability. This increases the cost for grid operators and also limits the amount of wind energy allowed in a country's energy mix, also known as wind penetration.

Integration with energy storage has been suggested as a solution for integration of renewables [6, 35]. Energy storage systems have the main functionality of balancing the mismatch between generation and load demand. Excess generation can be stored, avoiding energy dumping or preventing the interruption of the operation of a plant, and used during periods of excess demand, smoothing the electrical output and possibly preventing starting the operation of other power plants.

The main storage options available with current technology are chemical batteries, hydrogen fuel cells, compressed air, flywheels, pumped storage, thermal storage and electromagnetic storage (supercapacitors) [4, 6]. A database of energy storage projects is presented by [9], accounting for a total of 175 GW of installed capacity for all operational projects and technologies available. Figure 2.4 presents a comparison between different types of storage technology, their scale and storage duration.

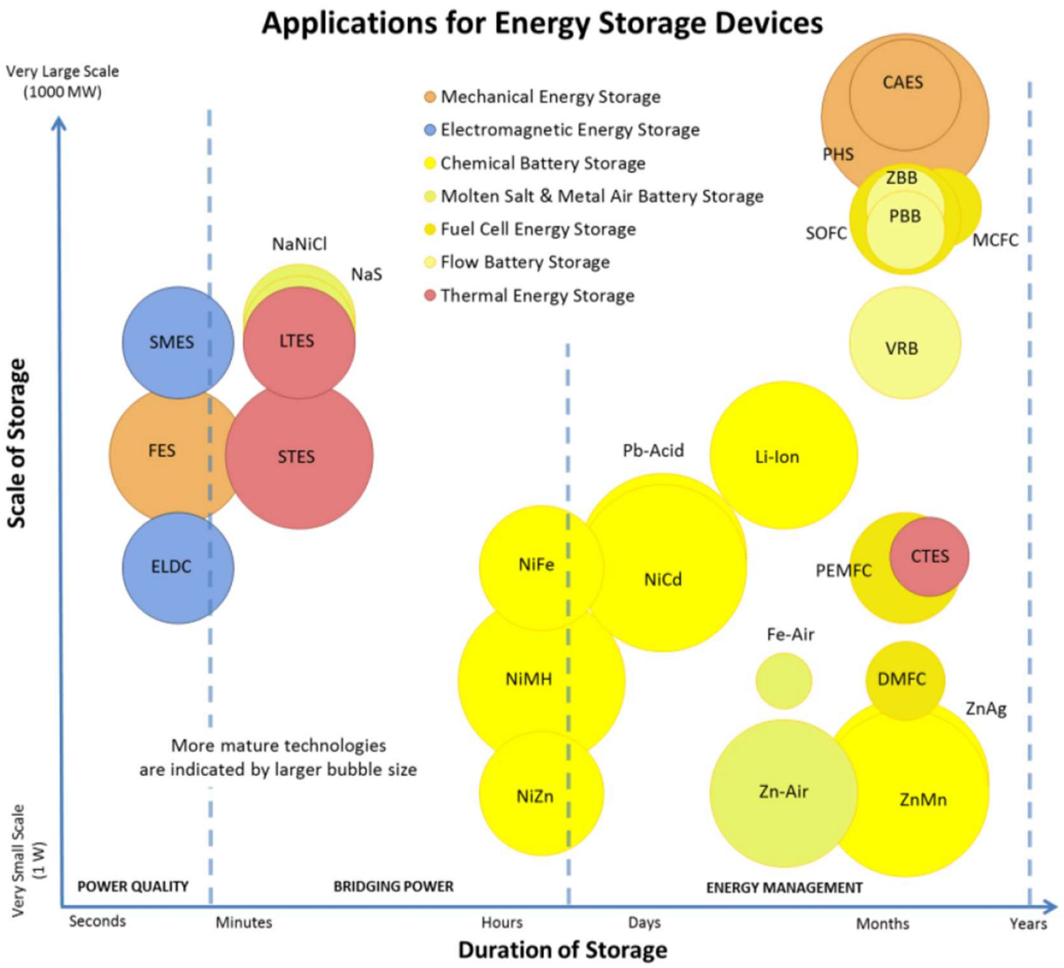

Figure 2.4 – Comparison of scale and duration of storage for energy storage applications [6].

As seen in Figure 2.4, the alternatives for energy storage are divided between the scale of storage and the duration of storage. Short-term storage usually has power quality functions, suppressing less than a minute variations such as voltage sags and frequency fluctuations. Medium-term storage can have spinning reserve, peak shaving and load following functions, from the scale of minutes to a few hours. Long-term storage has energy management roles, providing time shifting and seasonal storage to the grid [36, 37].

Challenges related to large scale energy storage include large initial costs expenditure and low maturity of technologies, as PHES is the only economically proven large scale storage option available [6, 38]. In addition, any type of energy storage always incurs energy losses in the process and the round-trip efficiency is defined as the ratio of energy obtained over the amount of energy required to store the total energy.

Associated with wind energy, storage can also allow connection to weak grids, aside from reducing the output fluctuation from the wind farm [39]. Wind penetration could be increased with the association of energy storage technologies [35]. There are examples of applications for small-medium scale storage projects integrated with wind energy for most of the available storage technologies, including even a hybrid wind-hydrogen-diesel project at Newfoundland [40, 41]. Integration of wind energy with PHES is further detailed in Section 2.3.

2.3. Pumped Hydroelectric Energy Storage

2.3.1. Water Resource

Water is an abundant substance which follows a natural cycle of evaporation and precipitation on the planet's surface. For hydropower applications, the natural flow of the river at the proposed site must be studied. To limit the region of study, a catchment area is normally defined as "as the area upstream from a certain point in the water course that contributes to flow when precipitation falls" [42].

Since the water flow conditions change with position and time, empirical methods, averages and statistical analysis are normally employed [42]. The average flow at a certain point will vary significantly with seasons, as the location experiences variable precipitation and evaporation. Historic measured data is usually available from measuring stations, which can be related to the studied region with similar characteristics.

To determine important flow rate values for a hydroelectric scheme design, exceedance curves are usually constructed from available data. These curves allow visualization of typical flow values which are likely or unlikely to be exceeded at the studied location at any time. The design flow of a hydropower scheme, which is used for designing the electromechanical components, is firstly decided with the analysis of exceedance curves and may be changed later to improve the economic performance of the project. Typically, environmental restrictions will also require the hydropower scheme designs to leave a minimum environmental flow release at the location at all times, limiting the energy extraction to minimize environmental impacts on the region [43].

2.3.2. Regular Hydroelectric Generation

2.3.2.1. Overview

Hydroelectricity refers to electrical energy converted from water's kinetic and pressure energy [44]. It is a clean energy source with mature technology, being the renewable source with largest installed capacity worldwide: 1,212 GW in 2015 [45]. Moreover, hydroelectric potential still exists worldwide, as a projection of almost 2,000 GW installed by 2050 is presented by [46].

Electricity generation via hydropower is renewable, doesn't consume fuels and produces little or no GHG emissions on generation phase [43]. Hydro schemes can have a long life span, exceeding 50 years of operation, and are associated with flood control and irrigation benefits [25]. Negative environmental impacts associated with hydropower are the alteration of water quality, sediment accumulation, alteration of the river bed, slit accumulation and impact on wildlife [25, 43, 47]. In addition, examples of social impacts of hydroelectricity are displacement of population, impact on transportation and fishing and creation of jobs, as 1.5 million jobs are associated with large and small scale hydroelectric projects worldwide [21, 43].

Hydropower is classified by its scale, being micro and mini hydro generally referring to less than 1 MW installed, small hydro generally attributed to schemes between 1 MW and 10 MW capacity and medium and large hydro for over 10 MW, although different criteria may be used [43]. Furthermore, two distinct topologies are identifiable: schemes with reservoirs, which may store water to overcome periods of little natural water flow, and run-of-river schemes, which have little or no storage, relying on the river natural flow to generate electricity [43].

Hydro schemes with reservoirs are exposed to seasonal and daily variation of the reservoir water level. When excessive generation is required, as in peak load periods, or during prolonged periods without rain to replenish the reservoirs, the amount of water available for generation may be insufficient to match the load. Consequently, other power plants may have to start operation, which may increase the costs of energy supply [22].

The main constituents of hydroelectric scheme are a dam or weir, a penstock, and a powerhouse that hosts the turbogenerator group. Figure 2.5 displays the schematics of a small run-of-river hydroelectric power plant.

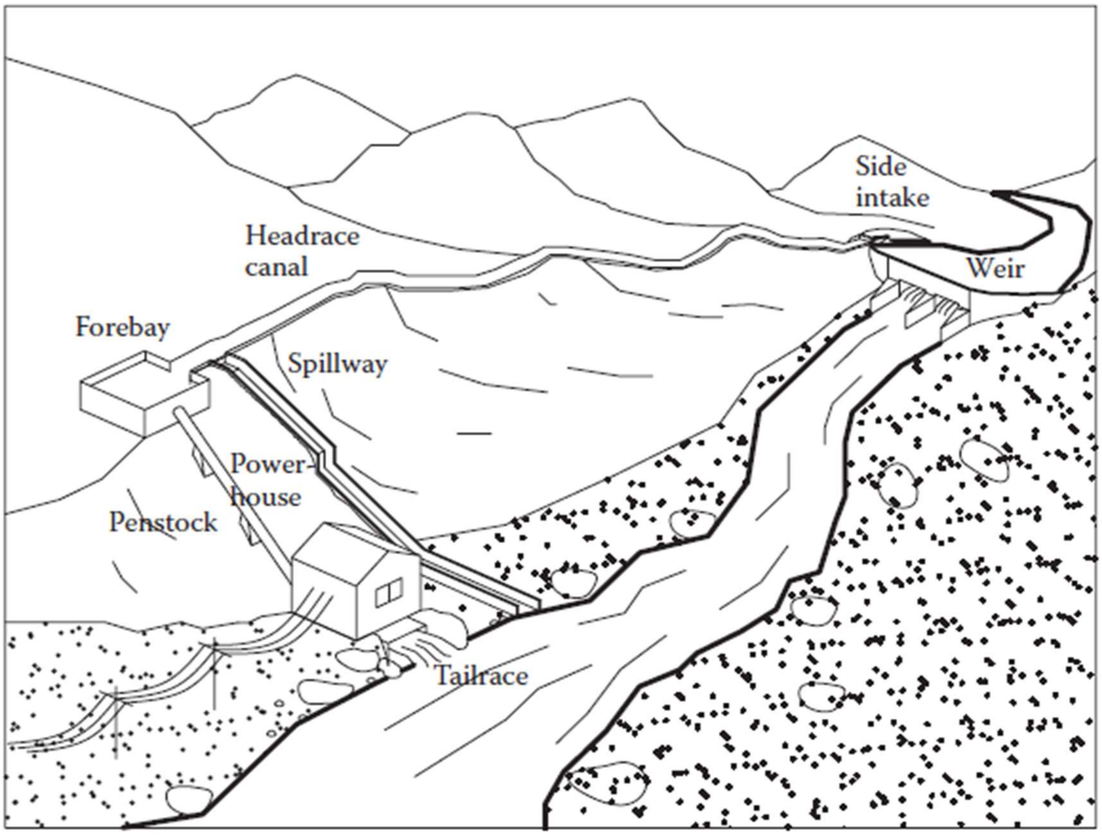

Figure 2.5 – Schematics of a run-of-river hydroelectric scheme [43].

The electrical power output of a hydroelectric scheme is given by Equation 2.8, adapted from [25]. The gross head of the system is equal to the height difference between the intake and the centreline of the turbine at the powerhouse [43]. The net head is equal to the gross head of the system minus the equivalent losses in the pipes due to friction and other losses.

$$P_{ele,hydro} = \rho g H_N Q \eta_t \eta_g \qquad \text{(Eq. 2.8)}$$

The calculation of losses during the water conduction from intake to the powerhouse involves a decision on the type of pipe and its diameter, which is a compromise between costs and losses. Increasing the pipe diameter will decrease losses but increase costs, and vice-versa. Normally, the choice of the penstock aims to limit total penstock losses to 10% of the gross head [43].

The final design of a hydropower scheme may involve an iterative process, adjusting characteristics of the scheme such as the penstock length and position of the powerhouse to obtain the best techno-economic solution available. Typical costs for large hydroelectric schemes are within the range of 1,000-3,500 US$/kW or approximately 750-2700 £/kW (with an exchange rate of 1 £ = 1.32 US$ [28]) and 2,500-3,000 US$/kW (2,250-2,700 £/kW) for small schemes [48, 49]. However, costs for remote locations can exceed 3,500 US$/kW (3,150 £/kW) with grid connection costs [48]. [50] also provided equations for cost determination of electromechanical equipment for small hydropower plants.

2.3.2.2. Types of Turbine

Different alternatives are available for turbines in hydroelectric applications. The choice of which turbine depends on specific characteristics of the chosen site, depending mostly on the available head and the design flow.

The two main categories of hydro turbines are reaction and impulse turbines. Impulse turbines use nozzles to increase the water speed before reaching the turbine blades, which extract the kinetic energy of the water [43, 51]. Most common types of impulse turbines are Pelton, Turgo and Crossflow. Reaction turbines have the runner immersed in water, extracting energy from the change in momentum and direction of the water [43, 51]. Francis, Kaplan and Propeller are the prevailing designs of reaction turbines. A third group of turbines applies to very low head hydropower applications. These VLH applications are generally for heads of less than 3.2 m and may be attractive for limited environmental impact and economic reasons [43].

Typical ranges of operation for each type of turbine are presented in Table 2.1, in terms of the specific speed. The specific speed allows the selection of the appropriate type of turbine, based on its rotational speed, head and power ratings, being defined in Equation 2.9. For this equation, adapted from [43], the hydropower scheme power is given in kW, the turbine rotation in RPM and the net head in meters. Figure 2.6 also presents the illustration of the main types of turbine available for hydroelectric applications.

$$N_s = N \frac{\sqrt{P_H}}{H_N^{\frac{5}{4}}} \qquad \text{(Eq. 2.9)}$$

Specific Speeds for Various Turbine Types

Turbine Type	N_s
Pelton	10–50
Turgo	20–70
Cross-flow	20–80
Francis	80–400
Propeller and Kaplan	340–1200

Table 2.1 – Specific speed ranges for each type of hydro turbine, adapted from [43].

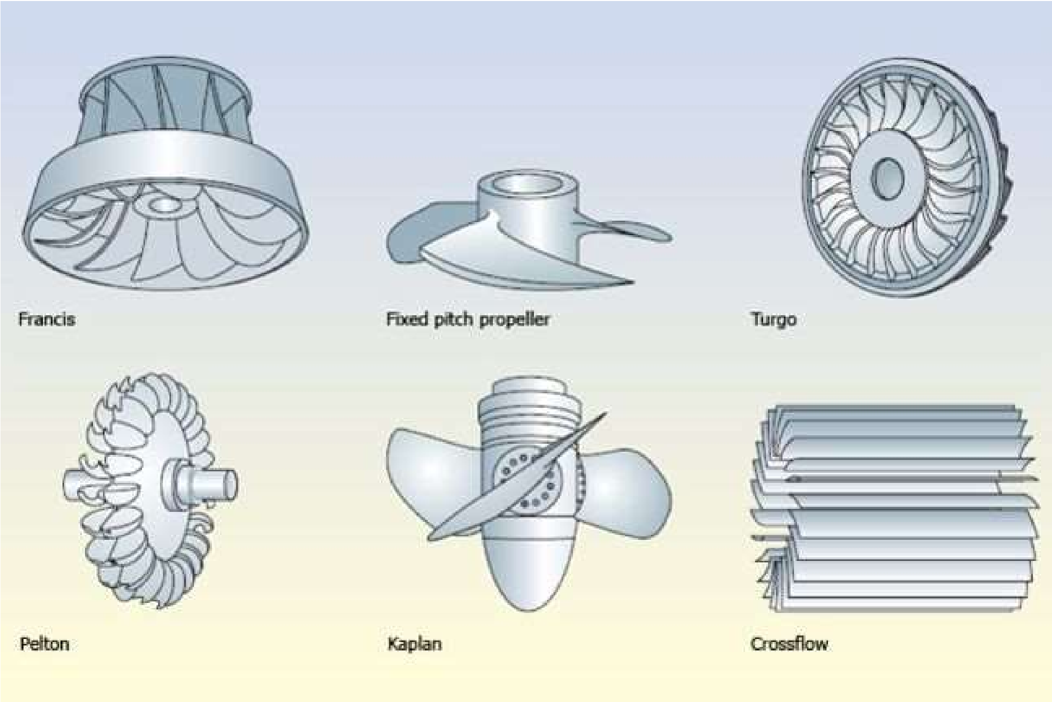

Figure 2.6 – Types of turbines for hydroelectric applications [25].

The final type and number of turbines is defined for the specific site conditions, head, flow and economic appraisal of the project. On a real project, a design is initially proposed and then different alternatives are considered, so that the project is modified to reach the best economic result possible, in an iterative process [43].

2.3.2.3. Types of Generator and Control

The generator choice part of the iterative process for finding the best techno-economic option available. Particularly for hydro applications, the turbo-generator group usually operates with fixed speed, as the governor adjusts the flow input depending on the electrical load and balances the changes in the angular rotation of the turbine [43].

The most common alternatives are the synchronous generator and the induction generator. The former allows control of the power factor, as the excitation system can be adjusted. The latter is a cheaper option but doesn't allow power factor correction [52]. Usually, large hydropower plants use fixed speed turbogenerator sets, as the variation of the total head is not significant. Variable speed operation is also an alternative which increases the range of operations of the system, as discussed by [53].

The control of water which enters the turbine is performed by a governor, which adjusts the water flow into the turbine to keep the rotational speed of the turbo-generator group constant [43]. Electronic load controllers are also an alternative for small scale hydropower applications, with faster response time and lower cost [43, 54]. Hydroelectric projects are also required to assess detailed studies about grid stability and power quality issues, which are not part of the scope of this study.

2.3.3. Pumped Hydroelectric Energy Storage

2.3.3.1. Overview

PHES systems are a modification of conventional hydroelectric plants, which allow pumping and gravity water flow between two reservoirs of different heights [55, 56]. Consequently, the system can pump water from a lower reservoir to an upper reservoir, storing potential energy for use when electricity demand is higher, and generate electricity letting water flow down to the lower reservoir [57].

For a pumping system, the amount of power consumed by the pump is given by Equation 2.10 and the specific head Y is also given by Equation 2.11, being subscript d for the discharge nozzle and subscript s for the suction nozzle. Both equations are adapted from [58].

$$P_{ele,pump} = \frac{\rho Y Q}{\eta_{pump}\eta_m} \qquad \text{(Eq. 2.10)}$$

$$Y = \frac{p_d - p_s}{\rho} + g(z_d - z_s) + \frac{c_d^2 - c_s^2}{2} \qquad \text{(Eq. 2.11)}$$

Main applications of the PHES system are to shave off peak load demand, to take advantage of different energy prices, provide frequency regulation and reactive power for voltage control [59]. In addition, "its quick start capabilities make it suitable for black starts and provision of spinning and standing reserve" [57].

Total numbers for PHES applications are difficult to find, as they are usually included with hydropower. [14] reported around 129 GW of installed capacity worldwide in 2010, while [9] presents a figure of 176 GW of installed capacity on 2017. [60] states that "Few high-head pump-turbines with rated capacity above 300 MW are yet in service" and more experience is required to understand the economy of scale and costs for these schemes. The technology has received increased interest recently, with the main drivers being the developments of renewable energy and liberalized markets, which demanded an increase in energy reserve of the grid, security of supply and generation for peak power periods [57].

Environmental and social impacts of PHES are generally similar to hydropower. However, [61] highlights the more frequent change in reservoir levels, changes in circulation pattern and a higher risk of spreading species, along with other particular impacts of pumped hydroelectric energy storage schemes.

PHES schemes have gross heads typically in the range of 30 m to 750 m [59]. The design flow is decided based on the best economic output of the project, considering the time of storage, plant capacity, losses and other variables. The number of hours of storage is also limited by the size of the upper and lower reservoirs and can vary greatly from 4 h to more than 20 h [9, 59].

There are different classifications for pumped storage projects: a closed-loop or pure plant always relies on pumped water to generate electricity in the discharging period; a pump-back plant uses a combination of pumped water and natural inflow of a water body [57, 62]. A PHES scheme may also have different topologies for the electromechanical components, as detailed in Section 2.3.3.2. [60] displays a table with PHES project contracted until 2010, being the vertical-axis reversible pump-turbine the most common configuration.

To date, PHES is regarded as the being the most cost-efficient and commercially proven large scale energy storage technology available [57, 62]. Such systems may have a useful life up to 50 years, while typical round trip efficiencies, given by Equation 2.12, adapted from [7], are within the range of 70-85% [14, 56, 63].

$$\eta_{RT} = \frac{P_{ele,H}}{P_{ele,pump}} \qquad \text{(Eq. 2.12)}$$

The main challenges of PHES schemes are finding a suitable location, high capital costs associated to new projects and late investment return periods, which can make projects unattractive to investors [64, 65]. Typically, the costs and economic viability of PHES projects are site specific [57, 60]. Capital costs within the range of 600-1000 €/kW (550-900 £/kW) are suggested by [65], while [62, 66] suggests 1500–4300 US$/kW (1100-3250 £/kW). Examples of factors that imply in the significant variation in costs may be the geographical characteristics of the site, grid connection availability, environmental costs [4].

2.3.3.2. Topologies

Depending on the system topology, a PHES may use turbines-generators and pumps-motors as separate units or combined into single units [60]. Using 4 separate units is a more complex and costly design, used on earlier PHES projects, but has a higher efficiency than combined designs, since machines could be designed for operation at a single point of maximum efficiency [59, 64]. Three units sets, with a reversible generator/motor connected to turbines and pumps on a single shaft, are also used where high heads are available [60]. This topology normally uses a synchronous machine, being both the pump and turbine designs optimized [65].

Binary designs, which have reversible turbine/pump connected to a reversible generator/motor, or 2 units on a single shaft, decrease the construction costs by 30% and typically has 2% lower efficiency [60, 64]. Reversible pump-turbines are generally Francis or Pelton types [65, 67]. Additionally, the use of vertical shaft topology instead of a horizontal shaft requires less physical space for the machinery of the plant [59]. Figure 2.7 presents the schematics of a PHES scheme, with a reversible pump-turbine and vertical shaft configuration.

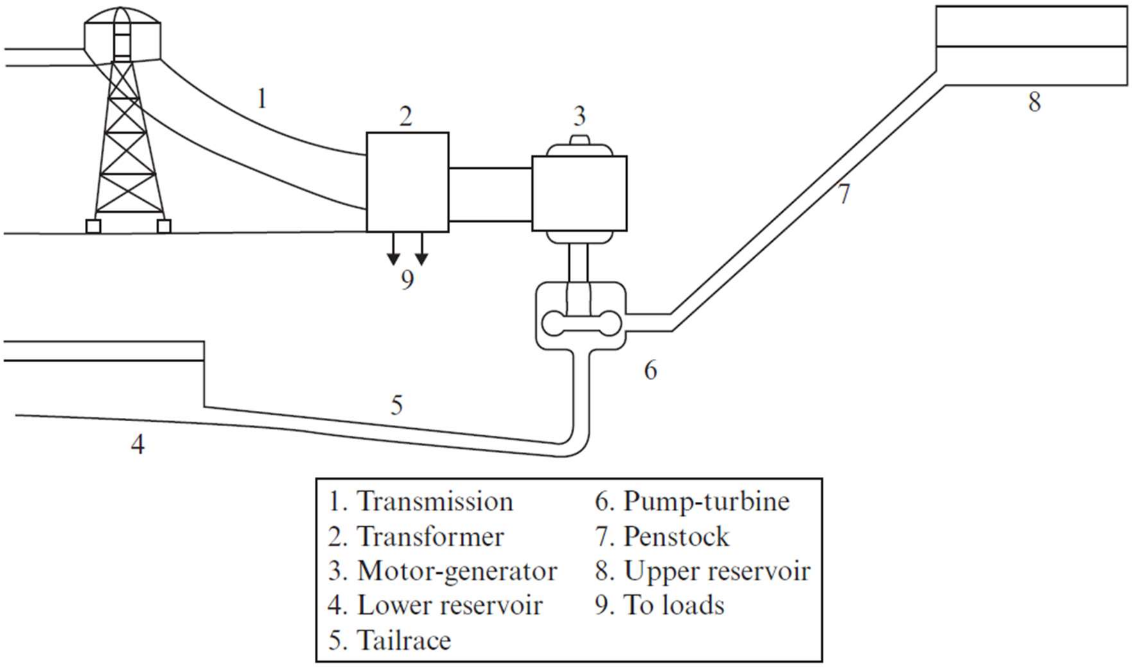

Figure 2.7 – Schematics of a PHES power plant with a reversible pump-turbine and vertical shaft [60].

A development of PHES schemes that can provide load-frequency control for the grid uses variable-speed pumps and generators. Variable speed enables control of the amount of power used by the motor/generator system, which can be used to stabilize frequency and power output and has been suggested as a way to modulate fluctuation from a wind farm [57, 59, 64]. A disadvantage of variable speed technology is that it has a higher capital cost than fixed speed alternatives [64, 68]. It should be highlighted that conventional fixed speed generators on hydroelectric schemes also adjust the generation power level and frequency with the governor, but variable speed machines “can rapidly change output through the electronic controls” [59].

PHES schemes are also being considered for underground and underwater energy storage applications. Underground schemes use an underground lower reservoir, possibly using abandoned mine pits as a potential site, as studied by [69]. Underwater schemes can store water deep into the ocean, using devices similar to concrete spheres, as detailed by [70].

Another important consideration for the PHES schemes design is how fast the system can come online and change its operation mode in order to support the grid. Typical start-up and changeover times for 2-units sets and 3-units sets of PHES schemes are presented in Table 2.2. However, these operational times depend on the topology and control of the scheme and the Dinorwig scheme, one of the largest in the world, “can contribute 1,320MW to the national grid within 10 s of demand” [60]. Using two penstocks and enabling pumping and hydroelectric generation at the same time is also a possibility, but it would increase the total costs of the project [10].

Mode change	Changeover times	
	3-unit sets s	2-unit sets s
Standstill to full-load generation	120	120
Standstill to full-load pumping	180	600
Full-load generation to full-load pumping	120	900
Full-load pumping to full-load generation	120	480

Table 2.2 – Typical PHES changeover times per set [60].

2.4. Hybrid Wind Generation with Pumped Hydroelectric Energy Storage

2.4.1. Overview

Combining wind energy generation with pumped hydroelectric storage is a relatively recent concept, introduced to take advantage of the storage capacity of the PHES technology to smooth the output variation of wind farms. This technology is described by its patent [71], and its schematics illustrated in Figure 2.8.

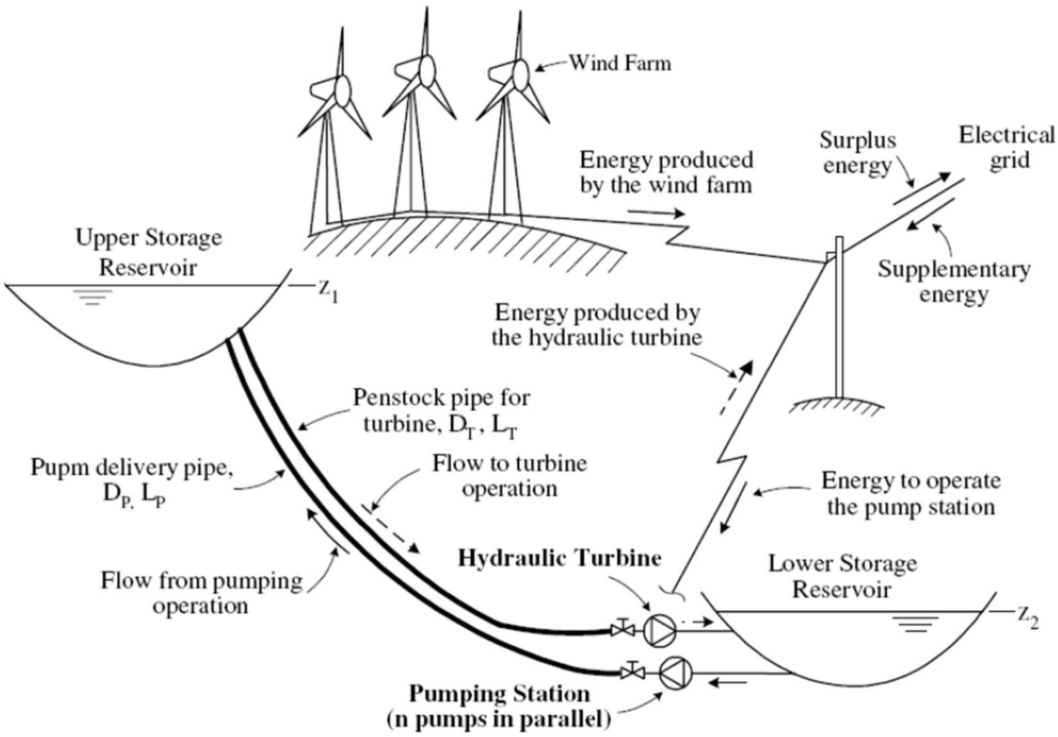

Figure 2.8 – Schematics of Hybrid Wind-Pumped Hydro generation [37, 72].

The principle of operation of the system is to use excess energy from wind turbines to pump water from the lower reservoir to the upper reservoir of the PHES plant. This stored water potential can be used to generate electricity during periods of low wind energy production, thus minimizing the output variability of wind energy.

Integration of wind generation and PHES has been discussed by several authors. [59] provided a full technical report on the integration of wind and PHES schemes. [63] compared PHES and chemical batteries storage options for balancing the output of a wind farm, achieving better economic results with the PHES scheme. [73] presented feasible techno-economic solutions for a wind-PHES system on Greek islands, comparing different capacities for the system. [74] achieved positive economic benefits with the integration of a hybrid wind-PHES system, taking advantage of different revenue tariffs on Portugal. [75] studied PHES as an alternative to reduce wind limitation during periods of high winds in Ireland, but found out that only when wind generation supplies more than 50% of Irish electricity the storage system would be economically justifiable.

Other potential benefits for hybrid wind-PHES systems are the increase in the average output of the wind farm, increasing the reliability of energy supply, less susceptibility to the shutdown of the wind farm due to grid constraints, the possibility of incorporating ancillary and energy management services. On the other hand, the identifiable challenges for these projects would be the large investments, late economic return, uncertainty associated with a new technology and finding suitable sites for implementation.

2.4.2. Topologies and Characteristics

A hybrid wind-PHES system would have similar design choices and topologies to those already presented for wind generation and PHES. The wind farm would still be designed to optimize energy extraction from the wind. However, the PHES scheme would be projected focused on smoothing out operation from the wind farm, which would require a fast response to sudden variations in wind speed, fast switching between pumping and generating mode and enough storage capacity to fulfil the desired objectives of the project.

The first possible topology to integrate two traditional large scale wind and PHES plants would be on a site with high wind speeds available and with a high natural head difference between two bodies of water. As the variation of the reservoir level would be small compared to the total head, fixed speed generation could be used, similarly to a conventional hydroelectric scheme. The application for this topology is very limited, as a site suitable for both wind generation and PHES is required. An example of this application is a project in the Canary Islands, as detailed in Section 2.4.3.

A second possible topology for integration of wind-PHES systems is having a low head hydroelectric power scheme, which could be installed near or even inside the wind turbine. This application is related to patent [76] and would have a greater range of applications than the aforementioned system, as the high natural height difference would not be necessary. In this case, the head of the scheme would be highly variable, possibly restricting the use to variable speed components only. This topology could be studied for offshore applications for example, but no applications of this topology have been found up to date.

Yet another alternative for integrating wind-PHES schemes could have smaller wind turbines, which would only be integrated (mechanically or electrically) to the pumping system and be used exclusively to pump water for the PHES scheme. Similarly to the previous topology, no application of this topology is currently being implemented.

As detailed in this study, the concept of using the wind towers as a vessel for water storage is a recent concept, which requires less area to be flooded for the upper reservoir of the PHES system. Limited literature is available for this particular application. Patents associated are [76], which specifies a water storage system within the wind turbine tower and also incorporates hydroelectric generation with two reservoirs at different levels, and [77], which details a hydrogen storage system within the tower. The main challenges associated would be structural safety concerns due to water pressure, the arrangement inside and near the tower (as it is normally used to pass the electrical cables and as an access for maintenance works), positioning and dimensioning of the tower, valves, pipes. As detailed in Section 2.4.3, a large-scale project, currently being installed in Germany, will test this type of water storage within the wind turbine.

2.4.3. Large-Scale Projects

Commercial large-scale implementations of hybrid wind energy and PHES systems have very few examples up to date. The only operational example of such system is the El Hierro project in the isolated grid of Canary Islands, as detailed by [13, 78-80]. The total project cost is 64.7 million euros (57.9 million pounds), having an installed capacity of five 2.3 MW wind turbines and four Pelton turbines of 2.83 MW. The pumping system is constituted by two 1.5 MW pumps sets and six 500 kW sets. The upper reservoir has a capacity of 380,000 m^3, with a gross head of 655 m. The total cost of the project is 64.7 million euros, partially subsidized by its government.

Data from this project is public and the performance of the project was analysed by [81]. Figure 2.9 shows the performance of the El Hierro project in its first year of operation.

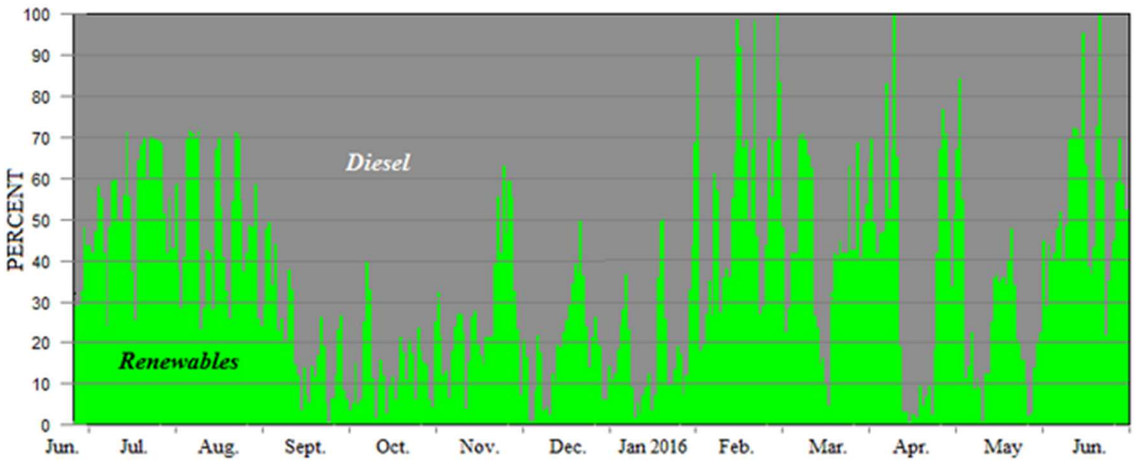

Figure 2.9 – Daily averaged percent of renewable energy supplied to El Hierro grid [81].

Reflecting on the performance of the system, it can be seen in Figure 2.9 that the results are irregular, as the renewable energy production is variable throughout the year and has prolonged periods with almost all energy supplied to the grid originated from diesel. Indeed, the hybrid power plant has not matched the performance expectations to date, as the first year of operation resulted in only 34.6% of electricity supplied via renewable energy, while [79] and [82] suggested the project could supply 68.4% and 64.6% respectively.

Causes of the project underperformance were the limitation of wind power to 7 MW with 11.5 MW installed, for grid stability reasons due to high wind penetration, and prolonged periods with low wind generation, which demanded diesel generation to supply energy for the island [81, 83]. Nonetheless, some positive results can be taken from the project, as 100% supply from renewable energy was achieved during some days of the year and 18,700 tons of CO_2 emissions of diesel consumption are avoided [13].

Another project had begun construction on the island of Ikaria, Greece, with an estimated power output of 2.4 MW of wind power and 3.8 MW of hydro power [84]. The project appears to have stopped during the construction stage, as [84] identified that the project was at risk due to funding and [85] displays complications found on the implementation of the project.

A further case of a hybrid wind-PHES project, to be commissioned by the end of 2017, is the Gaildorf power plant in Germany. It incorporates four 3.4 MW wind turbines, with 137 m of diameter and 178 m of hub height, and a pumped-storage system with a 16 MW hydroelectric plant, three reversible Francis turbines and two reservoirs [15, 86]. Similar to this study, part of the wind turbine towers are used to store water, being that the bottom 40 m of each turbine will store about 6,000 m^3 of water [87]. The wind turbines are placed within an outside reservoir, which stores an additional 34,000 m^3 of water, providing a total storage of about 160,000 m^3 and 70 MWh to the upper reservoir [87, 88]. The lower reservoir is located approximately 200 m below the wind turbines, connected via a penstock [87]. Total costs for the project are unavailable, but the scheme received 7.1 million euros funding from the German government [88]. Figure 2.10 presents the layout of the system.

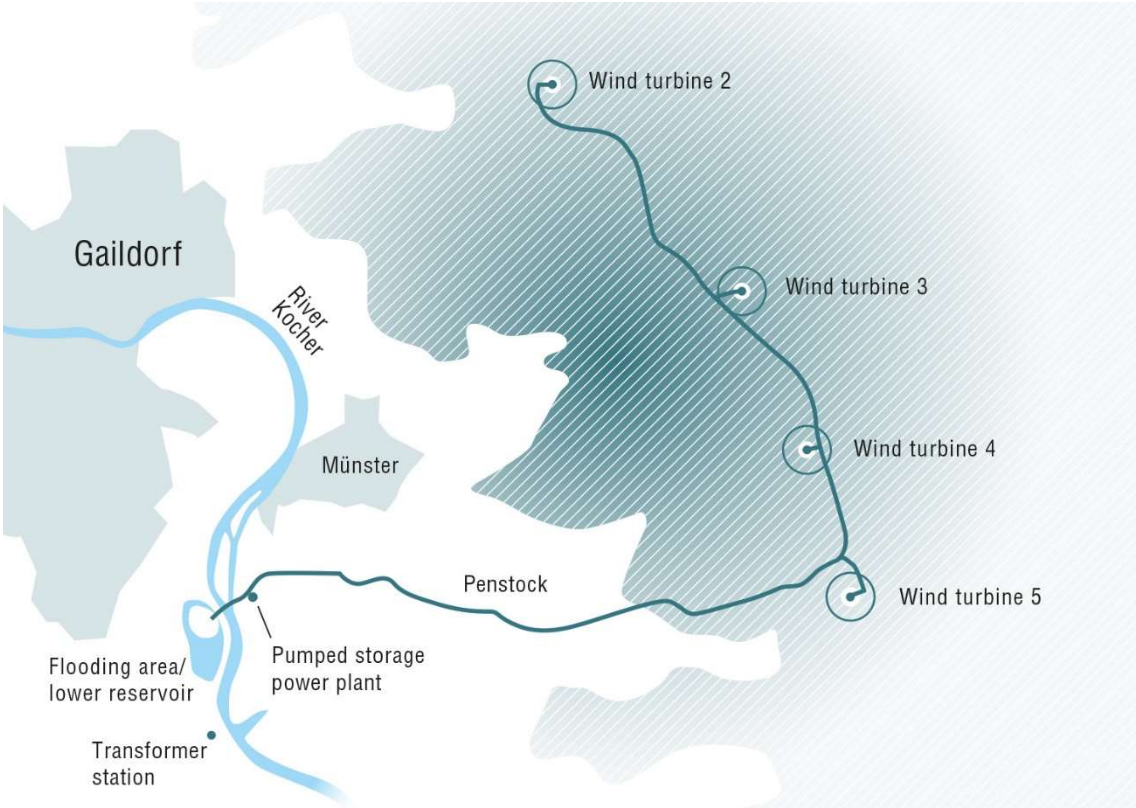

Figure 2.10 – Layout of the Gaildorf hybrid wind-pumped storage project in Germany [15].

2.5. Software Modelling of Hybrid Generation Systems and Energy Storage

Software modelling allows the analysis of a problem without the expenses of constructing a real-life model of a technology. It also enables doing repetitive and extensive calculations quickly in addition to allowing quick changes in the parameters and characteristics of the system.

Different options exist for simulating hybrid generation and energy storage systems. Specific design software packages are usually commercially available, which allow simulation of specific cases but can restrict the user interaction with the topology of the model to premade scenarios that are available within the software database. Examples of these types of software for energy storage are listed and compared by [89]. Other studies may prefer to describe a problem by a set of equations and use an optimization software to provide a sensitivity analysis and the best solution for a particular problem, such as [74].

Modelling types of software, like *Simulink*, allow the user to construct the model complete topology and allow more freedom to change the simulation scenarios. One advantage of the software is that the models already incorporate and calculate the physical equations that dictate the operation of components. *Simulink* also provides many examples of engineering models, as an example of [90]. There are also public databases, of different models created by other users, as an example of [91], which can be modified to adequate to a different problem. Another source of base models is [92] and its database [93], with models of renewable energy systems for engineering applications in *Simulink*.

There are a few examples of software modelling for studying the integration of wind and pumped storage systems. An analysis similar to this study is conducted by [12], which modelled a hybrid wind-PHES system in *Simulink* for the island of Ramea and concluded that a wind-PHES plant could be more beneficial than the current wind-hydrogen storage system at the island, recommending a full feasibility study of the plant. Another research by [94] used *Simulink* to create a model of a hybrid wind-hydro scheme using induction generators and voltage source converters, achieving power quality improvement and load balancing capabilities.

Another study, by [70], created a *Simulink* model for an energy storage PHES scheme, with offshore renewable energy applications and underwater energy storage. The ocean renewable energy storage system was tested to balance the energy from a hybrid 2 MW wind turbine and 3 MW wave energy devices scheme with a 1 MW PHES and 6.1 MWh storage system. Positive results are achieved, as the system is able to balance the output for 24 hours and with enough storage to keep providing balance for the next day. Nonetheless, the study lacks a long-term analysis of the system operation and an economic analysis, coming up short of providing insights about the feasibility of the technology as an investment.

2.6. Summary

A few studies have been conducted on hybrid wind-PHES systems, with one project already operational. The technology is a recent concept and different topologies and alternatives have yet to be tested. The concept of integrating storage inside the wind turbine tower is very recent, with only the pilot project in Germany and a few associated patents.

The performance of the only operational wind-PHES plant achieved some important objectives in supplying a full day of operation with only renewable energy, but long-term results came short of expectations. Since large-scale energy storage technologies have received increased attention with the expansion of renewable energy sources, it is important for these innovative projects to be studied and receive a full economic appraisal. However, since this is a complex project, only a few topologies or case-studies can be tested at a time. For this study, the next chapter introduces the assumptions and boundaries that the analysis is based on, the calculations and design choices made to reach the final topology and the final *Simulink* model.

3. Methodology

3.1. Introduction

The proposed hybrid wind-PHES involves an integrated knowledge of large areas of engineering. A software modelling of the operation of the scheme requires an investigation of several design choices and details of the project, which could on its own be a separate project. As an example, simple inputs for the project design, like the wind data analysis and the chosen layout for this study, would require a thorough analysis in order to provide insights for modelling and designing the system. All the calculations and design choices made to reach the final system configuration and the final model on *Simulink* for the simulations are presented in this chapter, beginning with the statement of assumptions and boundaries of the study. Some particular areas of study are limited due to time constraints or being outside the scope of the system.

3.2. Boundaries and Assumptions

Creating a software model representing a fully operational hybrid wind-pumped storage model is complex and some boundaries and assumptions are established to limit the work effort to areas relevant to the scope of the project. Hence, basic limitations and assumptions are listed in this section.

3.2.1. Assumptions

Any theoretical work can only represent partially the reality, as some components and physical characteristics are not fully represented due to their complexity or to save time on the study. Assumptions allow limiting the problem to a simpler and more efficient model to provide answers to specific questions.

The main assumptions considered while this study was carried are listed as follows. Other smaller assumptions for calculations are mentioned throughout the text.

- The grid is large and stable, with a frequency of 50 Hz, and modelled as an infinite bus, being able to accept the renewable energy supply from the proposed system at all times;
- Voltage levels for grid connection are UK standards of 11 kV and 132 kV;
- Water is incompressible and gravity is equal to 9.81 m/s^2;
- The storage within the wind turbine tower is cylindrical and with constant diameter;
- The lower reservoir can supply all the water needed for the storage on the upper reservoir;
- The wind turbine tower and the pipeline are able to handle the water pressure;
- The penstock and friction losses for the scheme were assumed as being constant percentages throughout the simulation, as calculated in Appendix A.5;

- The reservoirs on each wind turbine are located at approximately the same height from ground and are filled approximately equally;
- The flow rate for the turbine can be controlled with the governor and valves;
- The pump efficiency is assumed constant;
- The synchronous machine operating as motor/generator has constant efficiency;
- The wind data from North Harris is representative of the site, despite only 6 months of measurements. This wouldn't be possible in a real design, since only 6 months' data doesn't account for all seasons and the variation in wind speed;
- The measured data is applicable to a 1-2 km region around the measurement tower on North Harris, even though the site has complex topography and CFD studies would provide a better estimate;
- The logarithmic law correlation and the surface roughness used to correct the wind speed average from 50 m to 100 m gives a precise enough estimate for the wind speed. This wouldn't be applicable to real life, as the terrain is highly complex and CFD analysis would be best suitable, but it is the best estimate available with limited time available;
- Rayleigh probability density distribution is a good enough estimate of the wind probability distribution for that site;
- It is assumed that the wind turbine yaw system will be able to adjust the turbine orientation at all time, with no delays, so that the Rayleigh distribution from all wind directions can be used, instead of a detailed distribution for each direction;
- Wake losses are not considered and the same wind speed input occurs at all turbines at the same time in the model;
- The power lines between the wind farm and the PHES powerhouse are ignored, since they would have little effect on the simulation.

3.2.2. Scope of Analysis and System Boundaries

The scope of this analysis is limited to assess the costs of implementing a hybrid wind-PHES system, with water storage inside the wind turbines' tower, and the performance of the *Simulink* model.

The design case studies are selected to verify the performance of the system with the simulations and analyse the economic feasibility of the technology, comparing different settings. The three different cases for the simulations and cost analysis are listed below. They are selected to compare the cost of the wind farm with and without energy storage and compare the storage inside the tower to an equivalent artificial reservoir with the same storage capacity.

- Case 1: 8 MW wind farm without energy storage.
- Case 2: 8 MW wind farm and 4 MW PHES plant, with water storage up to 40 m inside the wind turbine tower.
- Case 3: 8 MW wind farm and 4 MW PHES plant, with a man-made lake that holds the same water volume as case 2.

Topics that were not detailed or considered in this analysis are listed below. These can be analysed on future projects.

- Structural analysis of the turbine tower is not carried;
- The type of valves and different alternatives for the pipes are not detailed, as an extensive iterative economic analysis is required;
- Hydraulic transients and water hammer considerations are not detailed;
- Cavitation considerations are not detailed;
- Wind data is not extrapolated to long term averages;
- Wind turbulence and other complex wind flow mechanisms are not considered;
- Load variations are not analysed, as the grid is modelled as an infinite bus;
- Electrical transient analysis is not detailed;
- Power quality analysis, such as power factor and voltage levels are not detailed;
- Environmental and social constraints of the wind-PHES scheme are mentioned, but not further investigated;
- Simulation of the prolonged performance of the system, to assess the energy production and full economic appraisal of the model is not carried due to time constraints, as explained in Section 3.5;

3.3. Wind Data Analysis

In order to test the *Simulink* model proposed in this study, real wind data from North Harris, UK, is used [95]. The measurements cover a period of 6 months between 2005 and 2006, measuring wind speed, direction and air temperature with 1 Hz frequency and at a height of 50 m above ground level. Filtering of inaccurate data was performed prior to the analysis and no prolonged periods without measurements were found.

The measurement site topography map is shown in Figure 3.1, from [96], being the anemometric tower identified as a cross and highlighted in yellow.

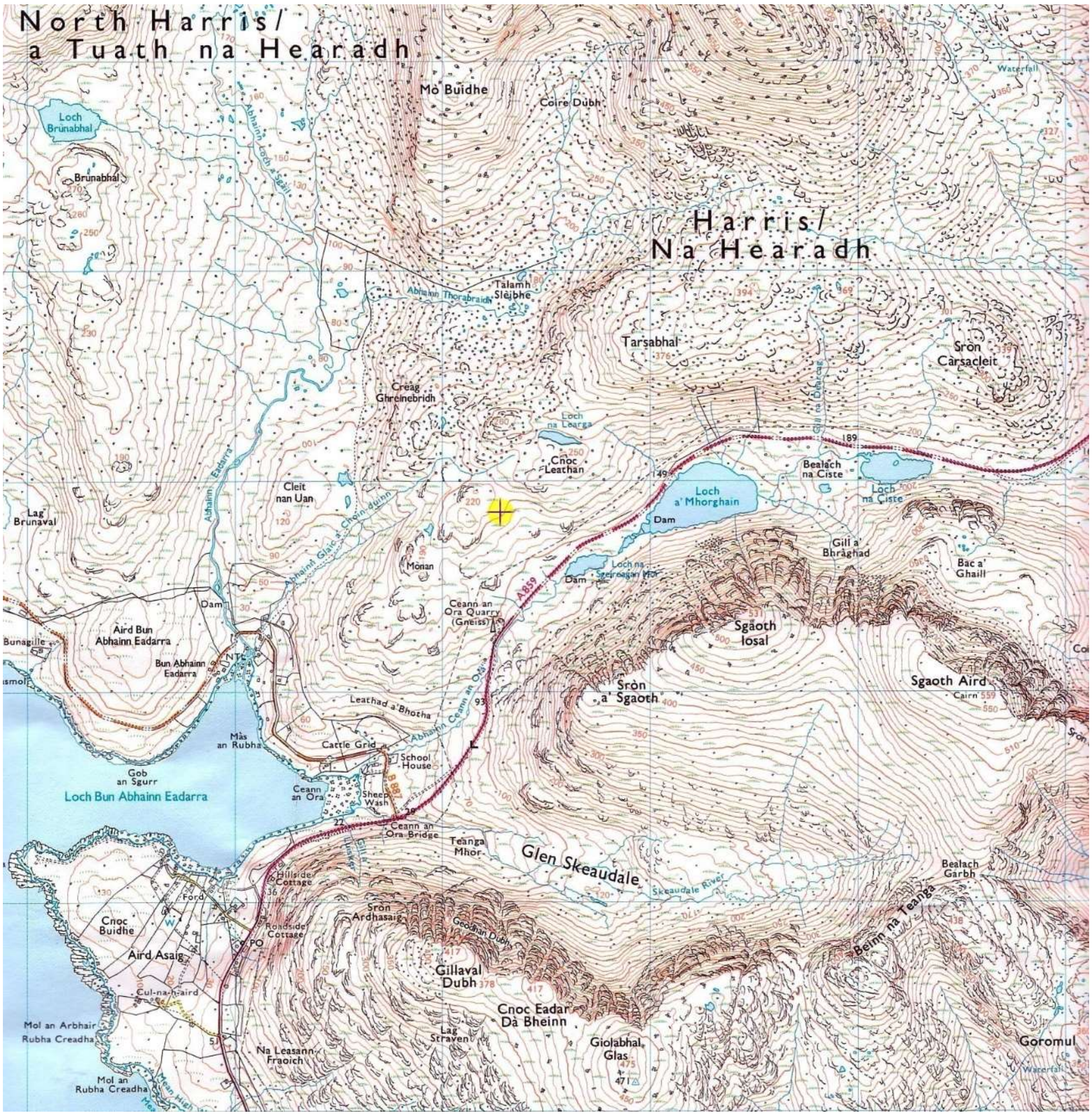

Figure 3.1 – Topography map of the wind measurement site in North Harris [96].

It is clearly visible that there are significant height gradients on the site, due to mountain ranges. Therefore, a CFD analysis of the site would be recommended for estimating the wind speed on locations different than the measurement spot. However, it is assumed that the measured data could be used for a region between 1 and 2 km for the wind farm proposed.

A brief statistical analysis of this data is carried in order to identify the average wind speed some other important wind speeds, used later for designing the system. A Rayleigh probability density distribution is used, which is described in Equation 2.2.

The main information of the wind data analysis is displayed in Table 3.1. The complete analysis can be found in Appendix A.3.

Period Measured	14/11/2005 to 25/03/2006
Average wind speed at 50 m	8.69 m/s
Highest wind speed measured at 50 m	54.26 m/s
Preferential wind direction	South/Southwest
Surface roughness used	0.1 m
Average wind speed at 100m	9.66 m/s
Highest wind speed estimated at 100 m	60.31 m/s
Wind speed surpassed 50% of the time at 100 m, from the Rayleigh distribution	9.1 m/s

Table 3.1 – Main results from the North Harris wind data analysis.

As seen on Table 3.1, the site has a high average wind speed of 8.7 m/s at 50 m and an estimated average wind speed of 9.7 m/s at 100 m. As explained on the assumptions, the logarithmic law is used for estimation of the wind speed at 100 m, which is not the best approach since the site has a complex topography, but it is the best estimate with limited time available.

An important parameter for the system design is the probability of exceedance of the wind speed at which the system delivers the design power output to the grid. As explained in Section 3.4, the design output is set as 4 MW, which corresponds to a wind speed of 9 m/s for the wind turbine used. This wind speed has an estimated probability of exceedance of nearly 50% according to the Rayleigh distribution used, which means that the average wind speed would surpass 9.1 m/s approximately 50% of the time, on average.

3.4. System Topology and Characteristics

3.4.1. Proposed System Characteristics and Purpose

As detailed in Chapter 2, one of the main advantages of the integration of the PHES system and wind farms is the capability of storing excess wind energy as water potential and using this to generate hydroelectricity on periods of lower wind output. This should enable the system to increase its average energy production, provide a more constant output to the grid, reduce both the amount of time with reduced output by the wind farm and the periods when the wind farm is shut down due to grid constraints.

The proposed system has a primary objective of delivering a constant design power output to the grid, limiting power output variations to the grid. However, the performance of the system is also limited by the amount of energy it can store, which will also be evaluated for the possible amount of storage inside the wind turbine towers. This is decided to test whether the PHES scheme with the proposed design and control strategy can efficiently balance the wind farm output fluctuations and increase the firm energy output of the wind power plant. As a single power output is set to be maintained at all times, the grid demand variation or market prices don't need to be modelled, which simplifies the *Simulink* model.

The reasoning behind this design is based on increasing the average wind farm power output and smoothing the power output to the grid. The average power for a wind farm can be estimated from the capacity factor, shown in Equation 3.1 and Equation 3.2, adapted from [16].

$$CF = \frac{E_w}{P_N t} \qquad \text{(Eq. 3.1)}$$

$$E_w = \bar{P}t = CF\, P_N t \qquad \text{(Eq. 3.2)}$$

As per [97], typical capacity factors for the annual operation of onshore wind farms in the UK have values between 26-29%. Therefore, the mean power provided by the wind farms is less than 30% of the rated power, with an output variation from 0-100%. With energy storage, the power fluctuation will be smoother and the average power increased. On this control strategy, the aim is to maintain a power output of P_{design} for the maximum time possible, which will probably not be possible for the whole operation of the scheme since the storage capacity is finite, but will increase the average power output to the grid and limit the variation of the output as long as storage is available.

To achieve this performance, the wind farm will be generating the maximum amount of energy it can deliver at all times. The operation of the PHES scheme will depend on the output of the wind farm, either using excess energy to pump and store water or generating electricity when wind generation is low. The ideal operation of the hybrid scheme is described in Figure 3.2, which highlights the possible operation zones of the system.

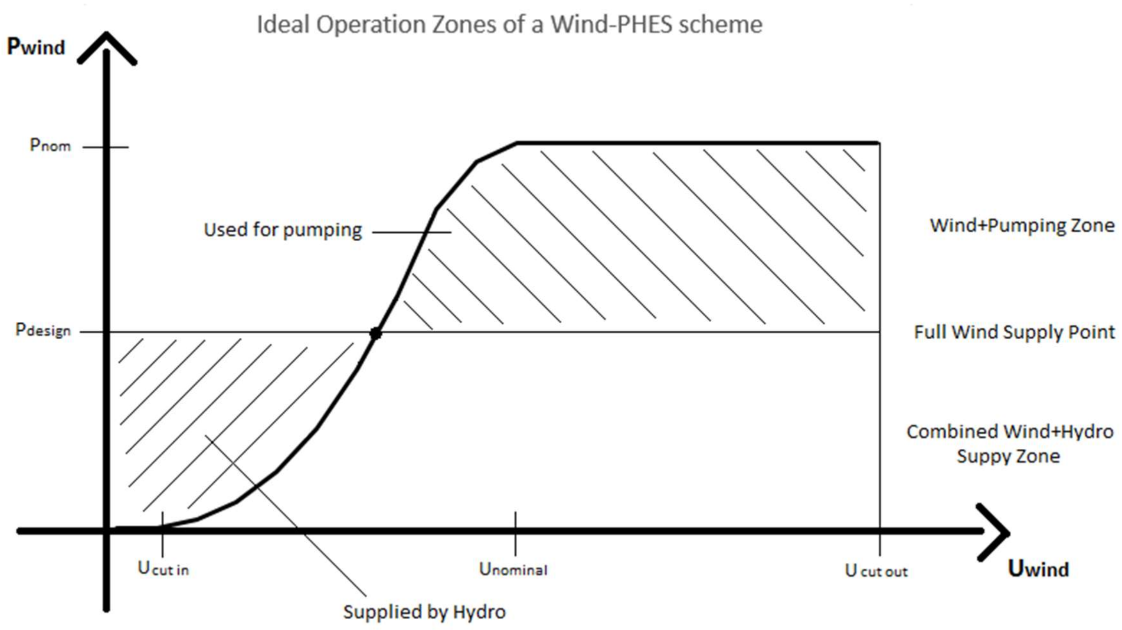

Figure 3.2 – Description of the operation zones of an ideal hybrid wind-PHES scheme.

As described in Figure 3.2, ideally, when the wind farm generates more than the desired output to the grid, pumping operation begins. When the wind output is below P_{design}, the turbines supply the difference, depleting water from the reservoir. Since P_{design} for the proposed system occurs at a wind speed that is likely to be surpassed around 50% of the time, the system would ideally operate around 50% of the time storing energy and 50% of the time using energy stored.

In a more realistic scenario, the pumps/turbines start-up time would be limited due to the required time to change the plant operational mode and delayed by the control system to avoid frequently switching the components on and off, which would increase losses and shorten their lifespan. The three different operation zones possible for the scheme are listed below. The operation zones are also graphically explained in Figure 3.3.

- If $P_{wind} > (P_{design} + P_{min,pumps})$, the scheme is in full wind supply plus pumping operation: the wind farm supplies 100% of P_{design} and provides energy for the pumping operation with the excess energy over P_{design}. If the reservoir level is completely full, energy is dumped with resistive loads;
- If $\left(P_{design} + P_{min,pumps}\right) > P_{wind} > (P_{design} - P_{min,hydro})$, the scheme is in full wind supply operation, the wind farm supplies approximately 100% of P_{design} and the PHES scheme is neither pumping water nor using stored water to produce electricity;
- If $(P_{design} - P_{min,hydr}\ ) > P_{wind}$, the scheme is in combined wind-hydro supply operation, the wind farm supplies less than 100% of P_{design}, with the hydroelectric scheme supplying the difference $(P_{design} - P_{wind})$. If the reservoir is empty, the scheme provides only P_{wind}.

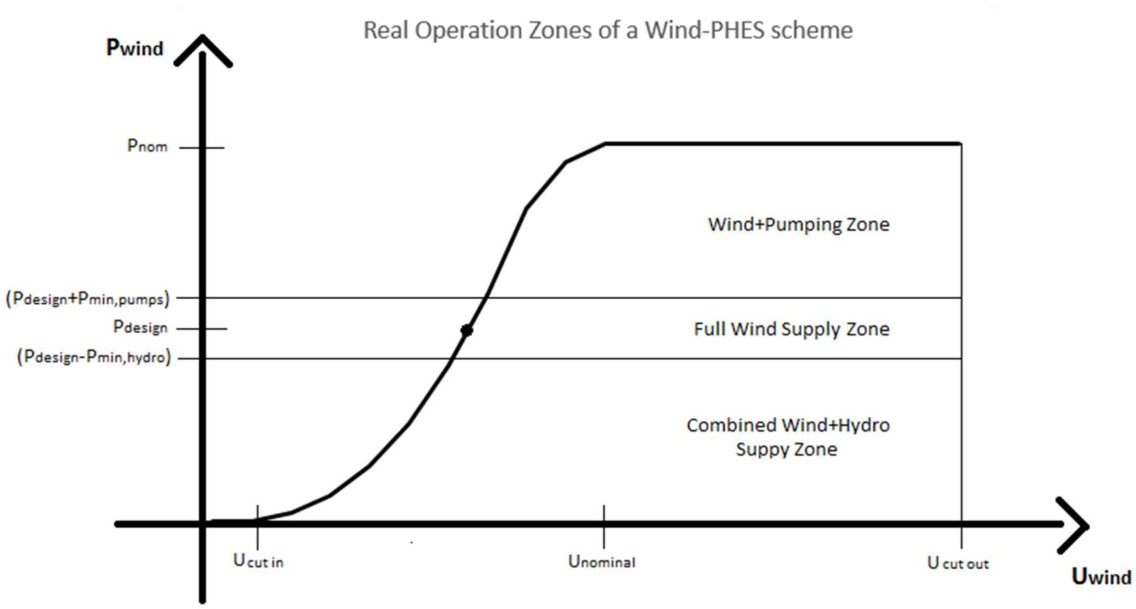

Figure 3.3 – Description of the operation zones of a real hybrid wind-PHES scheme.

Compared to other design strategies, this system has the advantage of being relatively independent of the grid, in case enough storage capacity is available for balancing the output at all times. Other control strategies could model the grid demand and pump water during periods when there is excess generation available for the grid, or take advantage of market prices, as an example of [63].

Some of the design constraints for the operation are: $P_{min,pumps}$, which would be the minimum energy available to start the pumps and would come from excess energy available from the wind farm; $P_{min,hydro}$, which would be the minimum power which would be efficient to start the hydro generation and would occur during periods of reduced power supply from the wind farm supply. Ideally, both variables would be close to zero and the operation of the pumps/turbines could start as soon as the power output from the wind farm deviates from P_{design}, but realistically, the start-up of the pumps and turbines could be delayed to prevent too much start-ups and shut-downs due to wind variation.

An important characteristic of the system would be the start-up times of both turbines and pumps. If the start-up time of the pumps or turbines is too long, the wind production could deviate significantly from P_{design} and the power output to the grid would be different than P_{design} for a prolonged time. This also interferes with periods of very high wind speeds, when the wind turbines are required to shutdown their operation due to structural concerns and the hydroelectric generation would need to start as fast as possible.

Another design constraint is the size of storage. The size of storage would influence the amount of energy that would need to be dumped in case the reservoir is full, the amount of time that the reservoir holds enough water for the hydro generation to be able to balance the wind output and the amount of time that the reservoir is completely depleted and hydro generation is not be able to balance the wind output. Ideally, the reservoir would be big enough to minimize periods of energy dumping and lack of hydro generation, but increasing storage size is costly. Realistically, a statistical analysis of wind data could provide inputs for designing an efficient storage size and the techno-economic assessment would verify the most cost-effective solution for the system.

Since the water reservoir is located inside the turbine tower, the space inside the tower would have to be redesigned to allow the whole area inside the tower to be used for water storage. This would require that the cables are repositioned, with three options available. The first would be in a conduit outside the tower, maximizing the storage capacity of the tower; the second would be in a conduit inside the tower, dedicated exclusively for passage of power and control cables and reducing the storage space; the third would be inside the tower and passing through the reservoir, which would not be ideal as capacitance effects could occur. In this study, in order to maximize the reservoir storage time, it is assumed that the cables are passed outside the turbine in an external conduit, but a structural and cost-benefit analysis could provide a better answer for this matter.

Furthermore, any other equipment located inside or nearby the wind turbine tower would need to be repositioned, preferably uphill of the tower or distant to prevent water damage in case of a reservoir failure. This means that the equipment would be repositioned in the nacelle and the substation of the scheme, with alternatives being either constructing an additional housing to accommodate the equipment or leaving them exposed to the weather, requiring extra ingress protection.

This system has a more suitable application for isolated grids, as it focuses on delivering a constant power output to the grid. Nonetheless, its application is extended to large grid applications as well, since the other objective of the scheme is increasing the average wind energy production of a wind farm without energy storage, in case the investment analysis of the scheme is positive and economically feasible.

The hydro system could also be used for spinning reserve purposes whenever it is not generating or consuming electricity, avoiding the shutdown of the turbine or pumps and providing support for the grid. This could be used to increase the revenue of the project, as the grid operator pays generators for this ancillary service [98]. However, this analysis was not included in the model, due to time constraints.

3.4.2. Topology

3.4.2.1. Wind Farm

The chosen topology for the model uses a large 8 MW wind farm, with 4 wind turbines of 2 MW and 100 m hub height, typical for 2 MW machines [17, 99]. The same wind farm is used in all 3 cases analysed in the cost assessment.

The wind turbine generator is a DFIG, rated at 2.2 MVA. The physical characteristics of the turbine presented by [100, 101] are used, including the stator and rotor inductance and resistances. However, an individual transformer per wind turbine is used to elevate the voltage from 575 V to 11 kV to reduce the nominal electrical current.

The summary of the characteristics of the wind turbine is displayed in Table 3.2. The wind turbine power curve, which was constructed from the *MATLAB* wind turbine model, is displayed on Appendix A.4.

Nominal turbine power	1.94 MW
Hub height	100 m
Rotor diameter	75 m
Cut-in wind speed	3.5 m/s
Nominal wind speed	12 m/s
Cut-out wind speed	27 m/s
Total moment of inertia	5.9×10^6 kg.m^2
Generator type	DFIG
Generator nominal power	2 MVA
Generator pole pairs	2
Generator speed range	900-2100 RPM
Transformer rated power	2.5 MVA
Transformer primary/secondary voltage	575 V/11 kV

Table 3.2 – Wind turbine characteristics for the simulation [100, 101].

The speed control of the wind turbines is shown in Figure 3.4. It is modified from the original *Simulink* wind turbine model and is similar to the one simulated in [100, 101], as the speed control curve is adjusted to avoid sudden large power variations in exchange of a suboptimal power coefficient and power output for the wind turbine at the start and before reaching nominal power.

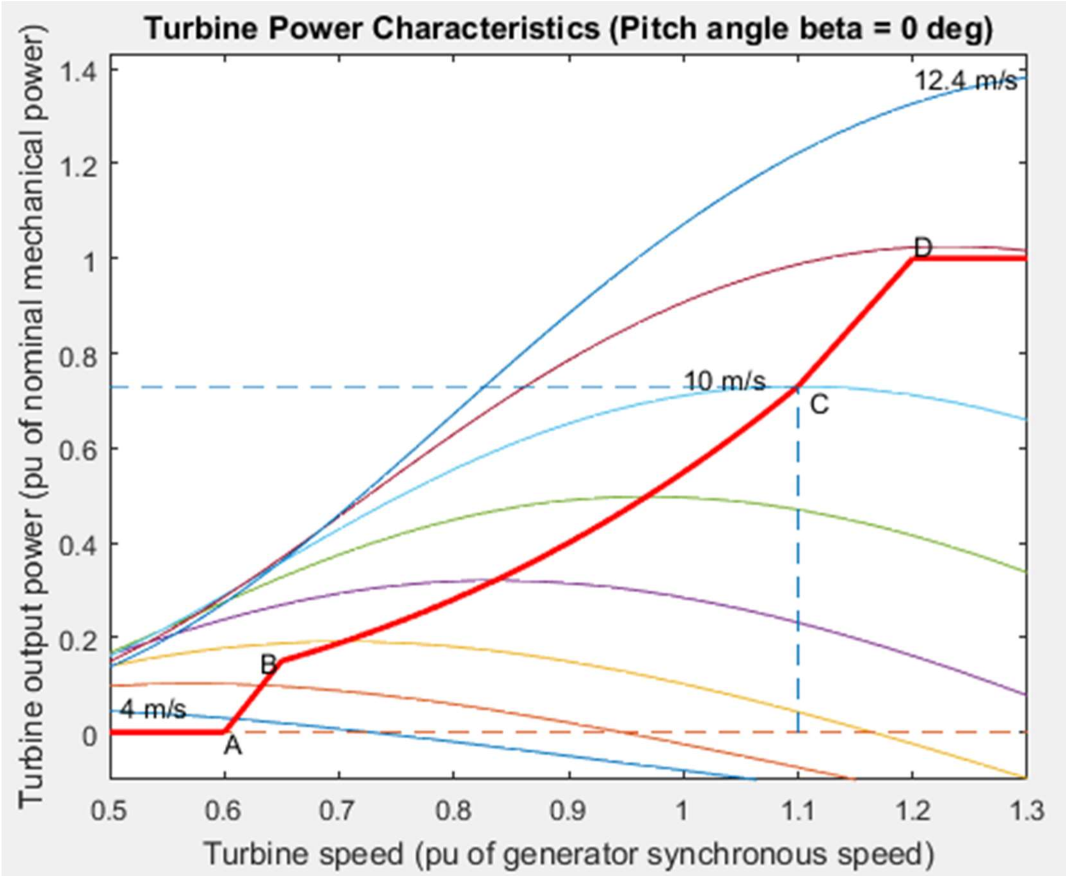

Figure 3.4 – Modified speed control curve on the wind turbine block on *Simulink.*

As seen in Figure 3.4, the generator speed varies between 0.6 pu and 1.2 pu of the nominal speed on normal operation. From point A-B and C-D, the power curve is adjusted for a smoother transition between operation points while obtaining a suboptimal power coefficient, as an example of [100, 101]. Between points B-C, the maximum power coefficient is still being tracked by the wind turbine.

3.4.2.2. PHES Scheme

As the wind data was taken from the North Harris site, the PHES system is based on the characteristics of the site near the anemometric tower. A brief positioning of the wind turbines was perfomed for estimating the length of penstock and costs of the system. Figure 3.5, taken from *Google Earth*, presents the layout used in this analysis, with the measurements tower indicated with a yellow marker, the wind turbines with a white marker, the powerhouse with a blue marker and the penstock indicated in red.

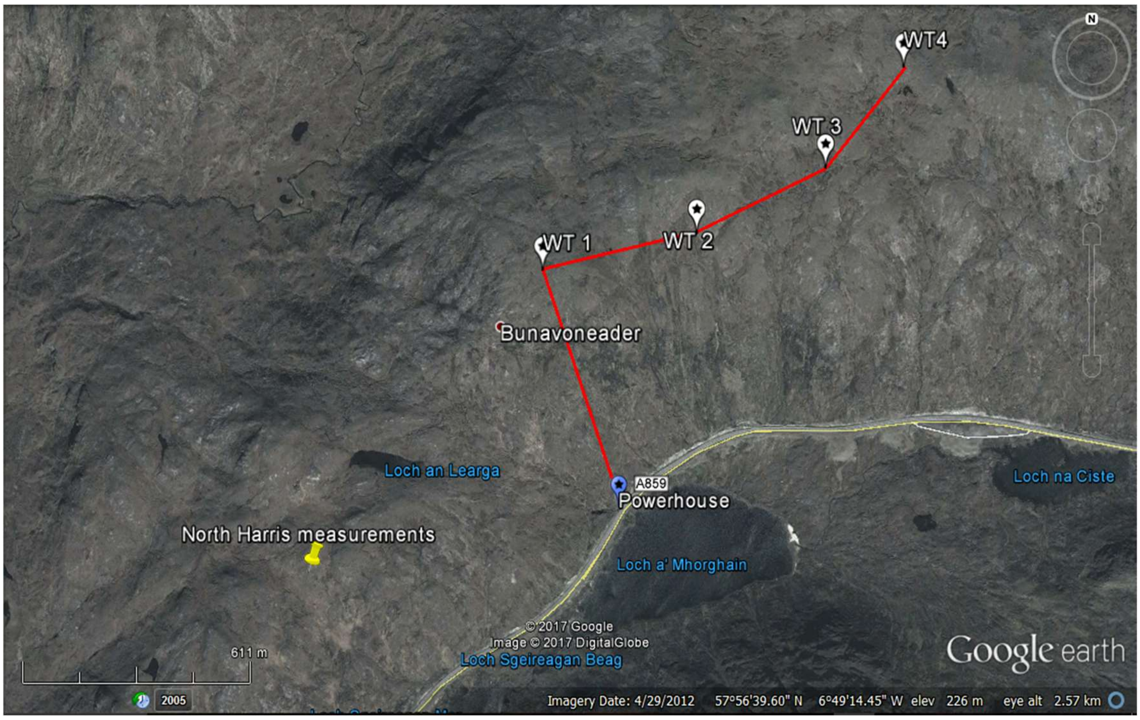

Figure 3.5 – Preliminary layout of the wind-PHES system used for the cost analysis, from *Google Earth.*

The wind turbines layout is based on the assumption that every turbine is spaced at approximately 5 rotor diameters apart from the next turbine and positioned at the same height, so that the reservoir on each tower will be filled at approximately the same rate due to Bernoulli's principle. Additionally, the site has various small water courses, which are avoided by the wind farm and the access tracks, but special precautions may be required from the environmental analysis.

The point of connection to the grid of the system is assumed to be at the existing 132 kV transmission line, which already passes near Loch a' Mhorghain and highway A859 on Figure 3.5 [102]. The access tracks to the wind turbines are assumed to have a length of 2.3 km, coming from a point near Loch na Ciste from the existing highway, from Figure 3.5, and passing on all wind turbines. This is assumed to be the same for all cases proposed.

The penstock trajectory is assumed linear between the towers and connecting to the powerhouse near the road and Loch a' Mhorghain. For cost estimation, it is assumed that the powerhouse building occupies an area of 200 m^2 and the powerhouse and the shared substation of the system would be located near the existing highway A859 on Figure 3.5. A simple analysis was carried to reach this layout and a real application of this system would require CFD analysis on the site, another measurement tower at the chosen hub height, to revalidate the wind speed data, micro-siting of the wind turbines to reach an ideal layout and a detailed analysis of the penstock route. However, this is the layout used for the cost analysis, due to time constraints.

The PHES system is proposed as a closed-loop system, taking water from a lower reservoir and storing it in the upper reservoir, which compromises the lower part of the tower of each wind turbine. A storage height of 40 m, similar to [15, 86, 88], is chosen for the reservoir. The total amount of water that can be stored in the turbine tower depends on the diameter of the tower. For a closed-loop PHES plant with cylindrical storage, assuming a constant diameter for the whole reservoir, the volume of water stored in the system and is given by Equation 3.3. For comparison purposes, the economic analysis will compare the cost of water storage on the turbine towers to creating a man-made lake which holds of the same water volume as the tower reservoirs.

$$V_{water} = \frac{\pi d^2}{4} h_s \qquad \text{(Eq. 3.3)}$$

The decision on the tower diameter is a compromise between the structural requirements and costs of the structure. For wind turbines, usually the tower diameter is greater at the base and reduced at the top, varying within a typical range of 2-5 m for steel towers and 2-12 m for concrete towers [16, 19, 103-105]. The base diameter is larger for higher rated turbines and higher towers and can be increased in case special adapters are used to interface with the foundations.

In case 1, without water storage, a concrete, slip formed tower with a base diameter of 8 m and a 3 m diameter at the top is considered, as the cost breakdown for the civil works is taken from one of the towers analysed by [104], for a 3 MW wind turbine. It is important to highlight that the 3 MW machine probably has a heavier nacelle and higher structural requirement, but for the same hub height, the tower design would be very similar to the 2 MW machines studied here.

For case 2, since a detailed structural analysis of the tower requirements was not carried, it is preferred to use a similar wind turbine tower to the one used in [15, 87, 88], which is designed to hold water as part of a hybrid wind-PHES upper reservoir. For this turbine, since the bottom 40 m of each turbine holds 1.6 million gallons of water, assuming that the volume is in US gallons and the base is a cylinder with a constant diameter, the reservoir diameter is about 13.9 m. Therefore, a constant 14 m diameter is used for the reservoir section of the wind turbine towers for case 2.

The total tower diameter for case 2 would be the reservoir diameter plus the wall thickness. Wind turbine towers have a wall thickness range between 10-80 mm for steel towers and 100-400 mm for concrete, being greater at the base and decreasing with height [17, 19, 103, 105]. However, since the tower would have increased structural requirements due to the water pressure of the reservoir, the wall thickness would have to be higher than the average wind turbine tower. Particularly, the thickness at the base is much greater, due to increased water pressure. From Bernoulli's principle, the pressure difference from the top to the bottom of the reservoir is equal to the water height times the gravity and the specific mass of water.

The storage height varies and the total pressure at the base will increase with the increase of storage height. The structural requirements for the wall of the wind turbine tower have a rather complex analysis and could be solved by more than one design choice. The design of concrete water reservoirs in the UK has to follow the standards BS EN 1992-3:2006 for concrete and BS EN 14015:2004 for steel [106, 107].

In this analysis, it was intended to compare the costs and application of both steel and concrete for the wind turbine tower and reservoir. However, the minimum wall thickness for steel water reservoirs, as calculated from [108] assuming atmospheric pressure on the reservoir, exceeded 1 m thickness, which is excessive and would require a custom manufacturing of steel plates. Therefore, the steel towers were discarded and only concrete towers are considered.

Another consideration for this analysis was to vary the height of storage inside the towers, to see the implication on costs and performance of the system. However, the calculation of the minimum structural requirement are not simple, since cylindrical water reservoirs are normally made very short with a wide diameter and some of the assumptions for using methods provided by [109, 110] may not be applicable, as the wall thickness would not be very little compared to the total diameter.

Therefore, since a full design of the concrete structure required by the tower is not the aim of this project it was decided to use a similar structure from [15, 87, 88] once again. Since the total tower diameter is 17 m at the base and the reservoir diameter is calculated to be approximately 14 m, the wall thickness of the reservoir section of the tower uses approximately 1.5 m concrete wall for 40 m of water storage. The type of concrete is assumed to have the same costs and properties as analysed by the concrete towers in [104] and other types of concrete are not analysed due to time constraints.

It is also assumed, for case 2, that the electrical and signal cables are passed outside of the wind turbine tower, with an external conduit. Another assumption is that the transformer of the wind turbine is located inside the nacelle, which is typical for large wind turbines, and all electrical measuring and protection devices are located at the substation.

For case 3, it is assumed that a circular man-made lake would be used as an alternative for the storage inside the towers. For 24,630 m^3 of storage, the proposed dimensions of the cylinder shaped reservoir are a diameter of 62.6 m and an approximately constant depth of 8 m and the reservoir would be positioned at the region between wind turbines 1 and 2 on Figure 3.5.

Loch a' Mhorghain is considered as the lower reservoir for the system. No information is available on the depth of the lake, but estimating the area of the lake on *Google Earth* with a triangular area and an average depth of 5 m results in a total volume of water of approximately 350,000 m^3. Since the amount of water used for storage in the upper reservoir is always less than 8% of the amount of water available, as it is about 24,630 m^3 with a full reservoir plus approximately 1,000 m^3 penstock water, environmental constraints would be limited.

The powerhouse is situated approximately 160 m above sea level. For this analysis, it is considered that the four wind turbines would be positioned at a height of approximately 360 m above sea level, resulting in a natural gross head of 200 m plus 40 m inside the wind turbines, a total of 240 m with full reservoir. The reservoir for case 3 is located at approximately 360 m above sea level and it has 8 m depth, giving a gross head of 200 m with full reservoir.

The decision on the type of pipe and its diameter would involve a trade-off between the cost of the pipe and reducing the losses. Since limited time is available, it was decided to have a common pipe type for the two energy storage cases analysed. This pipe is decided to be an HDPE pipe, type SDR 26 with 900 mm from [111] and calculation losses for cases 2 and 3 resulted in losses of 8.4% and 4.7% of the gross head respectively. This decision is based on an application with potable water and a pipe with reinforced material, with the diameter selected to limit the losses of the penstock below 10%. More details on the penstock losses are shown in Appendix A.5

Since a high head is available for the site and a rated power of 4 MW is required for the operation purpose of the system, a rated flow around 2.5 m^3/s is found with Equation 2.3 for both cases with energy storage, assuming a typical generator efficiency of 0.95 and a turbine efficiency of 0.9. For a high flow rate and a high head, a Pelton turbine is the best option for this case, coupled to a synchronous generator with 6 poles, a fixed speed of 500 RPM and 4 MVA rated power. Other turbine types like Francis with a higher rotational speed could have been evaluated, but the Pelton design is preferred due to the high partial load efficiency, typical of Pelton turbines [58].

Since the turbine will operate outside its designed power and its efficiency will drop, an efficiency curve for the turbine is used. The curve used is interpolated from real efficiency points for Pelton turbines, provided by [112, 113], and the comparison between the curve used and the real efficiency points is presented in Appendix A.5.

The pump is proposed to be separate from the turbine, making the PHES scheme a 3-set system. The same synchronous machine, operating as a motor, provides power to the pump. For this system, a concept used to allow faster switching between pumping and hydroelectric generation mode is the hydraulic shortcut, which connects both the pump and turbine with a high-pressure pipe [64]. This alternative also allows variation of the pump demand on the pumping stage and switching time of less than one minute between pumping and generating [64, 114]. The operation of this type of scheme is exemplified by the Austrian Kopswerk II, shown in Figure 3.6 from [114]. This topology was chosen because it allows variation of the pump demand and because separate units are easier and quicker to simulate on *Simulink*.

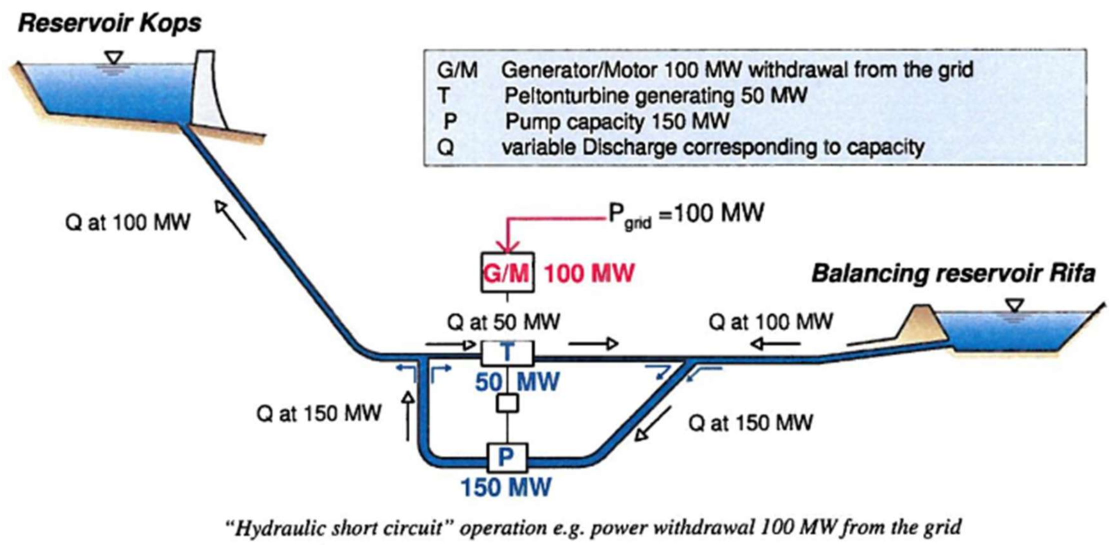

Figure 3.6 – Operation of the Kopswerk II scheme, from [114].

As seen in Figure 3.6, the operation of the Kops plant allows variation of the flow rate of the pump, consuming 150 MW in the figure, with simultaneous operation of the turbine and the pump. In that project, a Pelton turbine is used for generation and a Francis turbine is used for pumping.

This flexibility makes this scheme a good fit for balancing the variable wind output proposed by this study. Therefore, a 3-set topology with vertical shaft is chosen and, considering the high power rating of the pump, a 4 MW radial centrifugal pump is prosed as a pump for the system. Typical turbine efficiencies operating in pumping mode depend on the type of pump and the operation point. [58] displays a range of efficiencies for single stage, single entry radial pumps and the efficiency range suitable for the specific head and flow rate of this project is around 90%. Hence, the efficiency of the pump will be assumed constant at 87% for the operation of the pumping system, since the operational point varies from the nominal point.

The nominal pump flow, calculated from Equation 2.11 and Equation 2.12 with atmospheric pressure and a quasi-steady reservoir level, so that the speed at both nozzles are negligible, results in 1.64 m^3/s and 1.97 m^3/s for case 2 and case 3 respectively. This approach would have to be recalculated for a detailed design, with cavitation considerations, but will be carried forward for this preliminary design.

For both the hydroelectric turbine and the pump, more than one turbine/pump could be used, which would increase the reliability of the system and possibly increase the range of operation, since the minimum power for starting the first machine would be lower than the starting power of a single machine with higher rated power. However, for the sake of minimizing the simulation time and simplifying the model, one single machine of higher rated power is used for both the pumps and turbines and it is assumed that both start operation at 10% of their nominal power.

The characteristics of the PHES scheme, for the energy storage cases studied, are summarized in Table 3.3, highlighting that case 1 is based on the wind farm without energy storage. For the maximum storage time, it is assumed that 90% of the reservoir capacity is available.

Characteristic	Case 2	Case 3
Topology	3-set: Pump, Turbine, Motor/Generator	
Net head with full reservoir	228 m	183 m
Rated turbines flow	2.21 m^3/s	2.65 m^3/s
Type of turbine	2-Jet Pelton Turbine	
Specific speed [$kW^{0.5}/(m^{1.25}min)$]	38.2	34.6
Rated Pelton turbine power	4.78 MW	
Centrifugal pump type	Radial, single stage, single exit	
Centrifugal pump power	4 MW	
Rated pump flow	1.64 m^3/s	1.97 m^3/s
Rated synchronous motor/generator power	4 MVA (salient poles)	
Number of poles	6	
Rotational speed	500 RPM	
Voltage output	575 V	
PHES transformer rated power	5 MVA	
PHES transformer primary/secondary voltage	575 V/11 kV	
Total penstock length	1.52 km	0.53 km
Type of pipe	HDPE SDR 26 900 mm [111]	
Reservoir diameter and area	14 m and 153.9 m^2 each turbine	62.6 m and 3,078 m^2
Storage height	40 m	8 m
Upper reservoir capacity	24,630 m^3	24,622 m^3
Energy storage capacity	11 MWh	
Maximum storage time at rated turbine flow	2 h 44 min	2 h 19 min
Pumping time from empty to full reservoir at rated pump flow	3 h 45 min	3 h 07 min
Lower reservoir capacity	800,000 m^3	
Round-trip efficiency	71 %	

Table 3.3 – Summary of the characteristics of the PHES scheme, for the three cases studied.

As shown in Table 3.3, the storage time of the system is capable of regulating the power output of the wind farm on an hourly basis. With absolutely no generation from the wind farm, the system can hold the design power output for more than two hours, starting from a full reservoir. The different maximum heads of the two cases make for slightly different hydro designs, with different flow rates for generating electricity and pumping. Another highlight is the is relatively low round trip efficiency of the system, probably due to the usage of old efficiencies from past references, which are possibly taken from an even older reference.

Additionally, the rated flow of the pumping scheme is lower than of the hydroelectric scheme, as the efficiency of the motor/pump system takes its share of the available power. Four MW of electrical power is being delivered because the turbine is rated at 4.78 MW to account for the efficiency, but the pump will deliver less than the 4 MW electrical available, which accounts for the difference in the minimum reservoir filling time and the maximum storage time.

This possibly indicates that a better design alternative may be to select a slightly lower power design output to the system, as more power will be available for the pumps and less power be demanded from the hydroelectric scheme. Additionally, since lower wind speeds occur more frequently than higher speeds on a real wind distribution, the reservoir would slowly be depleted over time, instead of returning to approximately the same level. Possibly aiming for a pumping operation about 55-60% of the time and hydroelectric generation 45-40% of the time would be a better approach for the long-term operation of the proposed system. Nonetheless, this is the scheme used for the simulations, as limited time is available.

3.4.3. Control Strategy and Electrical Connection

The hydroelectric turbine is based on a fixed speed design, with the efficiency dropping when the operation point strays away from the nominal design power. This was chosen because the head of the scheme doesn't change significantly over with the reservoir variation and no model of a variable speed hydroelectric generator was readily available on *Simulink*.

The main supervisory control of the system has to control and monitor the system to achieve the system purpose detailed in Section 3.4.1. The main functions of the system are to activate the pump when $P_{wind} > P_{design} + P_{min,pumps}$, in case $V_{storage} < V_{storage,max}$, and the hydroelectric turbine when $P_{wind} < P_{design} - P_{min,hydro}$ and $V_{storage} > V_{storage,min}$. For the proposed system, Equation 3.4 provides the power balance for the power output of the system.

$$P_{output} = P_{ele,wind} + P_{ele,hydro} + P_{ele,pump} + P_{dump} \qquad \text{(Eq. 3.4)}$$

In case the reservoir is full and there's excess wind generation, the dump loads are activated to continue supplying approximately P_{design} to the grid. In case the reservoir is empty and there's lack of wind generation, the system only supplies P_{wind} to the grid. Additionally, the supervisory control waits for the flow rate on the penstock to be reduced to a safer flow rate of less than 0.2 m^3/s, equivalent to a 0.3 m/s water speed with the selected pipe, to start the pump or turbine during the switch from pumping to hydro generation and vice-versa, in order to avoid large pressure gradients on the penstock and valves.

To control the power output of the combined wind and hydroelectric supply zone, the governor control set point is set to fix the power error of the machine and the reference power is set to supply $P_{design} - P_{wind}$ while in operation. This would require a variable flow input to the turbine, which would be controlled by the governor and valve operation for the Pelton turbine. Additionally, the PID controller parameters of the governor have been adjusted, through a trial and error process, to achieve a better output response for the system. The final parameters used are $K_P = 8.119$, $K_I = 8.119$, $K_D = 0$.

As previously stated, a dump load is also used to dump the excess energy when the water reservoir is full. This is modelled as four controlled fixed power resistive loads of 0.5 MVA and no reactive power consumption. The power smoothing of these fixed power loads would not be optimal, as the power output can vary as much as 0.125 pu of the design power for the proposed system and more load of lower power can be used if a lower output variation is required. An ideal variable load was also considered, but fixed power resistive loads would be a cheaper solution and are considered in the cost analysis.

For electrical connection, a topology using the connection of the wind turbines, hydro generation and pumps on a common AC bus is chosen. This topology is preferred as it is simple to model in *Simulink* and would be the real-life equivalent of having the connection on the low voltage bus of the substation shared by both the wind and hydroelectric scheme. Power factor considerations are not detailed, but since both a DFIG and a synchronous machine are used, the power factor of the system would be adjustable.

For the connection of both plants on the shared substation, a voltage level of 11 kV is chosen, as it is typical for subtransmission in the UK [115]. For grid connection, the system would be connected to the existing 132 kV transmission line on the island of Harris, which is also planned to be connected to mainland UK grid [102]. Therefore, a transformer of 10 MVA and voltage ratio of 11 kV to 132 kV is used for the shared substation. Figure 3.7 presents the schematics of the electrical connection of the system to the grid.

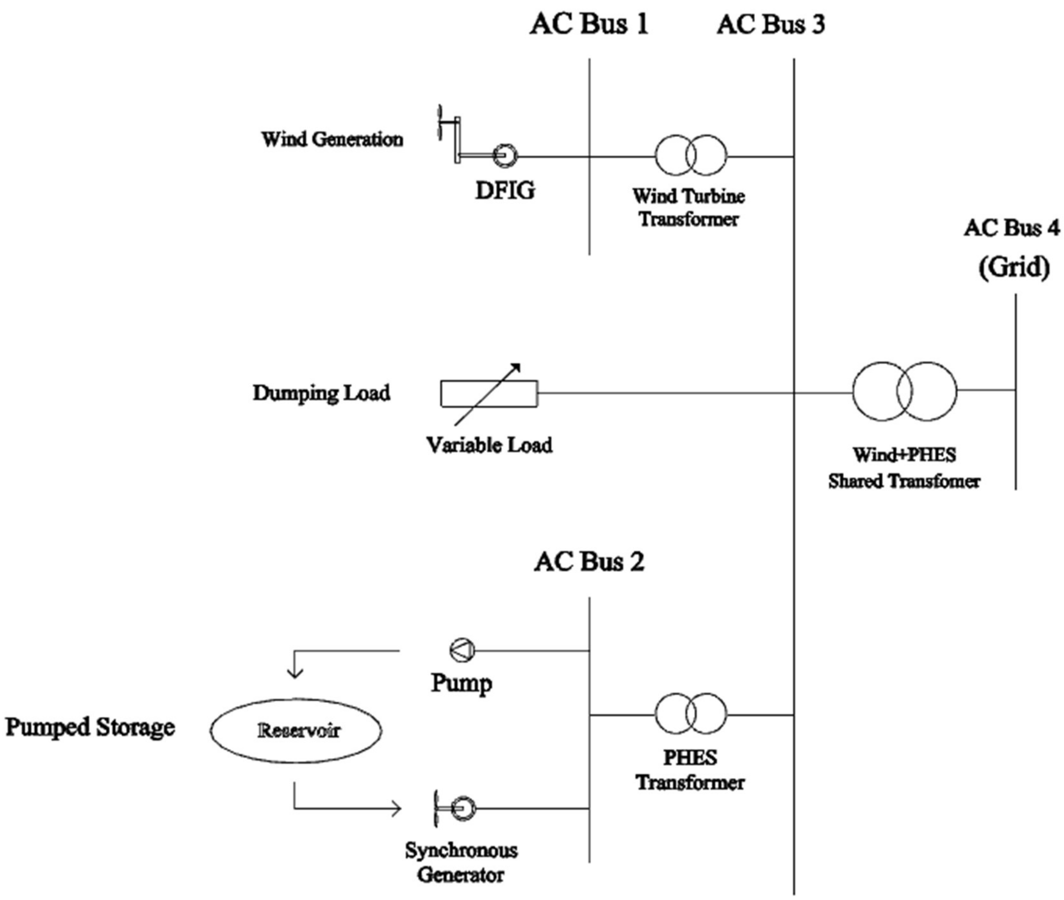

Figure 3.7 – Schematics of the electrical configuration of the scheme.

3.5. *Simulink* Modelling

3.5.1. Starting Point: Existing Models

Simulink models for wind farms are available from [93] and *Simulink* examples, which are available with the *MATLAB/Simulink* software. The base model for the wind farm used in this project was [90], *MATLAB* example "power_wind_dfig", which was chosen because it is recommended to simulate low-frequency electromechanical oscillations and long periods of simulation, which will be required to simulate the reservoir level fluctuations. This model is also based on a dynamic modelling study for wind turbines by [116].

This *Simulink* example has 2 other models of similar topologies, which employ a discrete type of simulation to allow visualization of harmonics and the dynamics of the control systems and are recommended for shorter periods of simulation, as explained by [117].

Figure 3.8 illustrates the unaltered wind model. It represents a wind farm, with 6 wind turbines of 1.5 MW with variable speed, variable pitch and DFIG generators, connected to the electrical grid. Transformers, loads, a fault simulator and transmission lines are also available for the starting model.

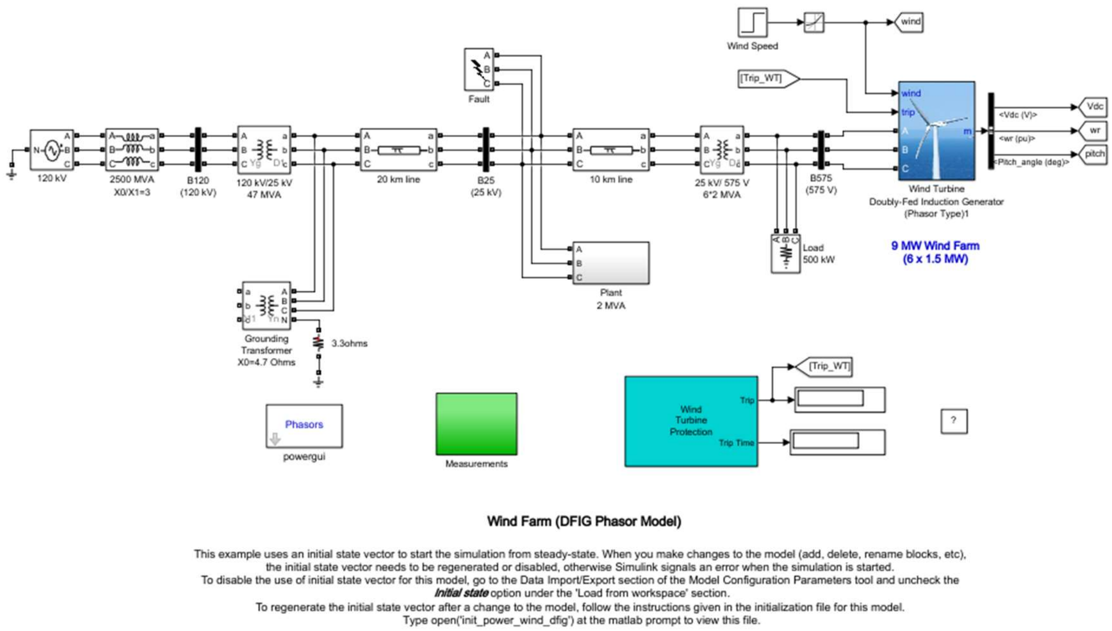

Figure 3.8 – Wind farm example from *Simulink* [90].

No specific pumped-storage model was found in public databases of *Simulink* models. Similarly, no hybrid wind-PHES model is publicly available, although a similar system has been simulated before by [12].

Conventional hydroelectricity models are available from [93] and also *Simulink* examples. The base model for the hydroelectric plant used in this project was [118], *MATLAB* example "power_turbine", which was used because it already models the governor and hydro turbine, with a synchronous generator and fixed speed operation. The modelling of the governor and hydraulic turbine system is shown in Figure 3.9, from [118], with an electronic control via the PID controller.

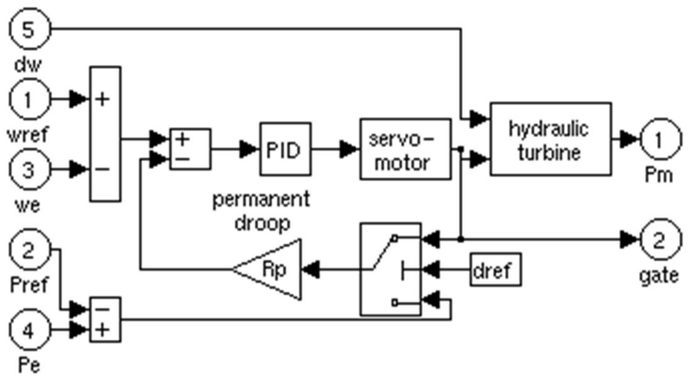

Figure 3.9 – Modelling of the governor and hydraulic turbine on *Simulink*, from [118].

The pumping system is based on a centrifugal pump powered by a synchronous machine, operating in motor mode, from the *Simulink* model [119]. The synchronous machine has same parameters as the hydroelectric turbine machine, as it is intended for them to be the exact same unit on the project. Using two separate machines with the same parameters proved a better alternative for the *Simulink* model, as the governor and control blocks for them are different.

Since a variable speed model of a synchronous machine isn't available and modelling the shaft and mechanical components of the scheme with the hydraulic shortcut strategy discussed by [64, 114] demands much simulation time and real time, it is decided to simplify the pump analysis and control the mechanical power output controlled to extract $P_{wind} - P_{design}$. This allows controlling the output of the pump and saves time modelling a pumping system as originally intended, with a shaft connecting both machines and varying the pump power with the turbine.

The reservoir part of the final model is based on [120], a *MATLAB* example available with the command "open_system('sltankrule')". This existing example simulates the operation of a cylindrical reservoir, with fuzzy logic controlling the input flow. Only the water tank part of this system was adapted for use on the final model.

3.5.2. Adaptation of the Hybrid Wind-PHES Model

To combine all components needed from the wind generation, hydro generation, water storage and water pumping models, several alterations were made to the original models and components were added and removed. Table 3.4 summarizes all the alterations done to reach the final model.

Alteration	**Description**
Frequency set to 50 Hz	Change in frequency of all electrical components from 60 Hz to 50 Hz, to adequate to UK standards.
Voltage levels set to 11 kV and 132 kV	Change in medium voltage and high voltage levels to adequate to UK standards and the voltage level of the transmission lines near North Harris.
Split wind farm model from 1 aggregated turbine to 4 different turbines	Represented the wind farm with 4 different turbines, which is more physically accurate than 1 aggregated turbine with 4 times the rated power. It allows different wind speed inputs at each turbine and modelling the wake effect on each one.
Model adapted to allow importation of wind data input from *Excel*, specific for each turbine	Added blocks to import data from Excel for each wind turbine wind speed input. Also added a gain block to simulate a percentage reduction in wind speed due to wake effects.
Changed simulation type of the Hydro model from "continuous" to "phasor"	Changed the "powergui" simulation type settings to "phasor", to adequate the same type of simulations as the wind farm model.

Alteration	Description
Integration of models into the same model, in different subsystems	Moved the hydro model into the wind model, created a subsystem for each model and connected them to a common bus.
Deleted extra electrical blocks which were irrelevant to the analysis	Deleted blocks which were not required for the current analysis and would only slow the model simulation, such as fault blocks, transmission lines, loads.
Imported the water tank model and adapted it to have a flow inlet from the pumping system and an outlet for the hydro turbine	Added the water reservoir part and altered it to allow flow from the hydroelectric turbine and to the pump. Additionally, mathematical and function blocks were added to calculate the flow according to the mechanical power input to both the turbine and the pump.
Added a synchronous machine to model the pump	The pump was modelled as a synchronous machine with a mathematical model for the centrifugal pump, with a controllable power output.
Changed reservoir storage capacity	Changed the dimensions of the reservoir to adequate to the full capacity of the turbine towers. To simplify the model, one reservoir with the full capacity of all turbines was used instead of one reservoir for each tower.
Added eight three-phase loads to dump excess energy from the wind turbines when the reservoir is full	Eight three-phase 0.5 MW load blocks were added to consume excess energy when the reservoir is full and the pump cannot operate. The load is also controlled to dump the excess energy from the wind farm over P_{design}.
Added a control system to deliver P_{design} to the grid at the maximum amount of time possible	Added multiple signal routing and conditional switching blocks to operate the system according to its design purpose.
Added a control system to switch off the pump and dump the energy when the reservoir is full	Added multiple signal routing and conditional switching blocks to switch off the pump and dump energy in case the reservoir volume reaches 90% of the maximum volume.
Added a control system to switch off the turbine when reservoir is empty	Added multiple signal routing and conditional switching blocks to switch off the hydroelectric turbine in case the reservoir volume reaches 10% of the maximum volume.

Alteration	Description
Altered the wind energy model to one transformer per wind turbine and added a transformer for both the pump and hydro generation	Added transformers to increase the voltage level and avoid very high currents from the energy generation. Additionally, the transformer would be positioned at the nacelle, which is common for large wind turbines.
Altered the wind turbine speed control curve	Alterations on the wind turbine speed control curve to adequate the operation points for the turbine proposed
Altered the parameters of the PID controller of the governor	Altered the parameters of the PID on the control system of the governor to get a faster response from the hydroelectric turbine.
Multiple signal routing blocks and measurement scopes added	Added multiple blocks to measure specific parameters of the system.

Table 3.4 – Summary of alterations done from the first models until the final model.

As shown in Table 3.4, multiple alterations were needed to reach the final model, being that all of them required testing and adjustments to achieve the desired operation of the system. All of the components use basic *Simulink* and *SimPowerSystems* blocks.

3.5.3. Final Model

The final model displayed in *Simulink* is presented in Figure 3.10.

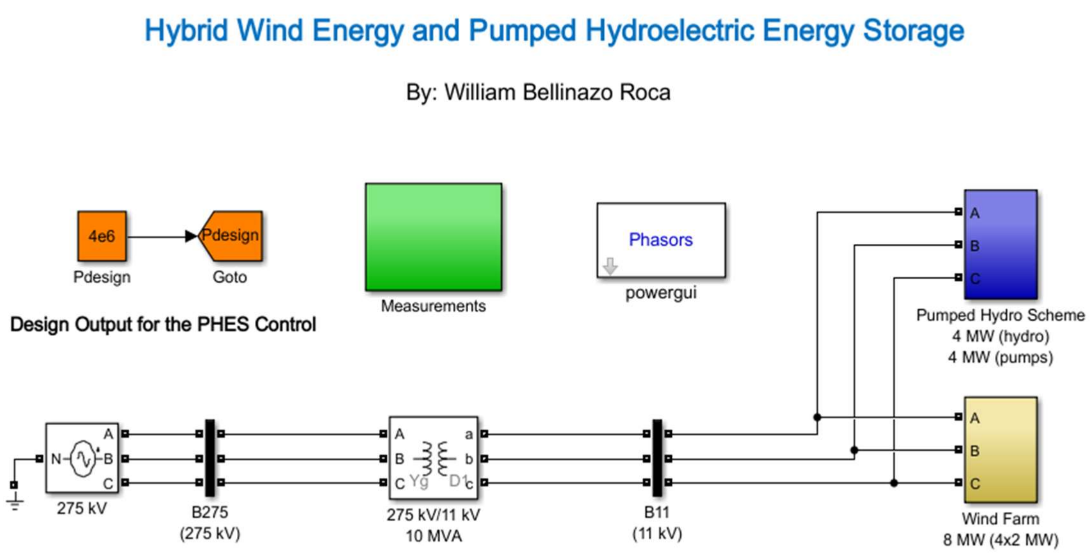

Figure 3.10 – Final model displayed on *Simulink*.

As seen in Figure 3.10, each of the models, wind farm and PHES scheme, are compromised inside two different subsystems. They are both connected to the same AC bus at 11 kV, located on the common substation of the system. As previously mentioned, a 10 MVA transformer steps up the voltage to 275 kV for the grid connection at the infinite bus.

The final model is available in the file "windPHES_final.slx", along with instructions for simulation with default parameters on the file "Instructions.txt". The same instructions are presented in Appendix A.1.

All three cases can be simulated by disconnecting the PHES scheme for case 1, changing the efficiencies for the penstock losses, water tank height and base area for cases 2 and 3, as both are modelled as cylindrical storages.

The control of the reference power input to the governor is also shown in Figure 3.11. The input power is determined by comparing the current wind energy output to the design power output and controlled switches determine the shutdown of the turbine when the reservoir is depleted, when the minimum power available for the turbine is not available and the start of the turbine only when the flow rate on the penstock to the pump has ceased, for safety reasons.

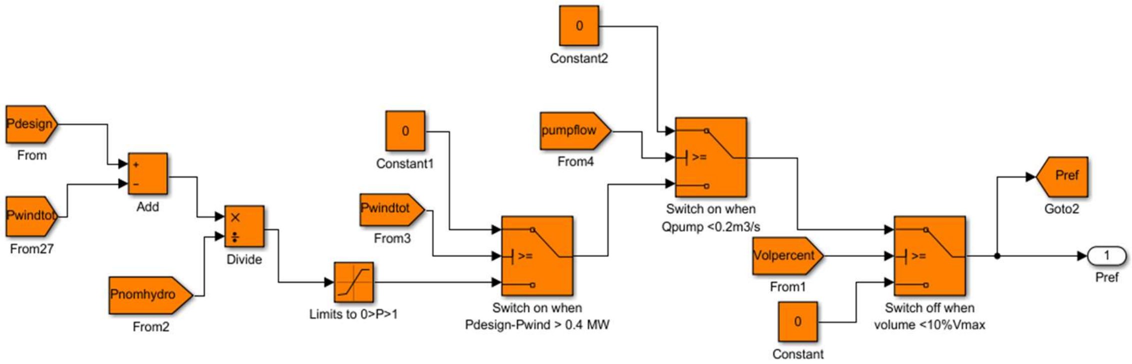

Figure 3.11 – Control of the reference power input to the governor of the hydraulic turbine.

Since the model allows wind input directly from excel and parameters of the wind turbines, hydroelectric generator, pump and physical characteristics of the system can be changed within the model, it is suitable for application on sites other than the one analysed in this study. However, this may require readjustment of the control parameters and other adaptations of the control system, in case another control strategy is used.

For an accurate estimation of the energy production of the scheme, accounting for periods when the reservoir is depleted and full and with real wind speed variation, the model would need to simulate the time scale of months and years of operation. Since for each simulation minute with real wind data, on an average computer, it takes between 1-15 minutes of real time to run the simulation, it is not possible to simulate the system for the full economic appraisal of the scheme. Additionally, since only 6 months of wind data are available, the simulation would not represent the full seasonal variation of the energy production.

Therefore, the simulations are set in a period of 12 hours, to test the basic functionality and performance of the model and the performance on short time periods and the economic assessment was limited to a cost analysis of the system and comparison between the different cases studied. Furthermore, the 12-hour simulations are carried with the “Accelerator mode” on *Simulink*, which slightly decreases the precision (less than 2% compared to the normal simulation) and resolution of the results but greatly improves the simulation time for long periods of simulation.

3.6. Summary

In this chapter, the methodology used for designing and simulating the hybrid wind-PHES scheme was presented. For the selected site with an average wind speed of approximately 9 m/s, an 8 MW wind farm with four wind turbines is used, with DFIG and one transformer per nacelle. The PHES scheme uses a 4.8 MW Pelton turbine and a 4 MW centrifugal pump.

Three case studies are selected for simulation and techno-economic assessment, case 1 with the wind farm without energy storage, case 2 with energy storage integrated on the wind turbine towers and case 3 with an external reservoir of the same capacity as case 2. The energy storage cases aim to deliver a design power output of 4 MW for as long as possible, with approximately 24,630 m^3 of water storage and 11 MWh storage capacity.

The final model incorporates the control strategy of inputting the difference between the wind farm power output and the design power to the governor of the hydro turbine, along with switches to limit the operation. The results of the simulations of this system are shown in the next chapter, followed by a brief economic analysis of the scheme. As limited time is available for the simulations, the simulation of months of years of operation is not possible and the full techno-economic assessment is limited to a cost analysis of the three cases proposed.

4. Simulation Results, Cost Analysis and Discussion

4.1. Simulation Results

The final model was simulated for the chosen simulation design case studies. The selected period of operation was between the days 14/11/2005 and 15/11/2005, with data from 19:00 to 7:00 corrected to 100 m, which had a minimum speed of 2.15 m/s, a maximum speed of 20.27 m/s and average speed of 9.01 m/s.

For the results analysis, this section is divided into the short-term performance, which shows the details of the dynamic operation of the system for the first 5 minutes of simulation, and the 12-hour simulation performance, which incorporates the full period of 12 hours of simulation time and the analysis of the energy production and variation of the reservoir level. All simulations start from steady state, with 10 seconds of constant wind, before being input with the real wind data. Additionally, both reservoir levels start with 50% of their maximum storage capacity.

4.1.1. Short-Term Performance

4.1.1.1. Case 1: Wind Farm Without Energy Storage

For the first case, the PHES system was removed from the model and the 8 MW wind farm was simulated. The wind input to the wind farm is shown in Figure 4.1, which is the same wind input to all short-term simulations.

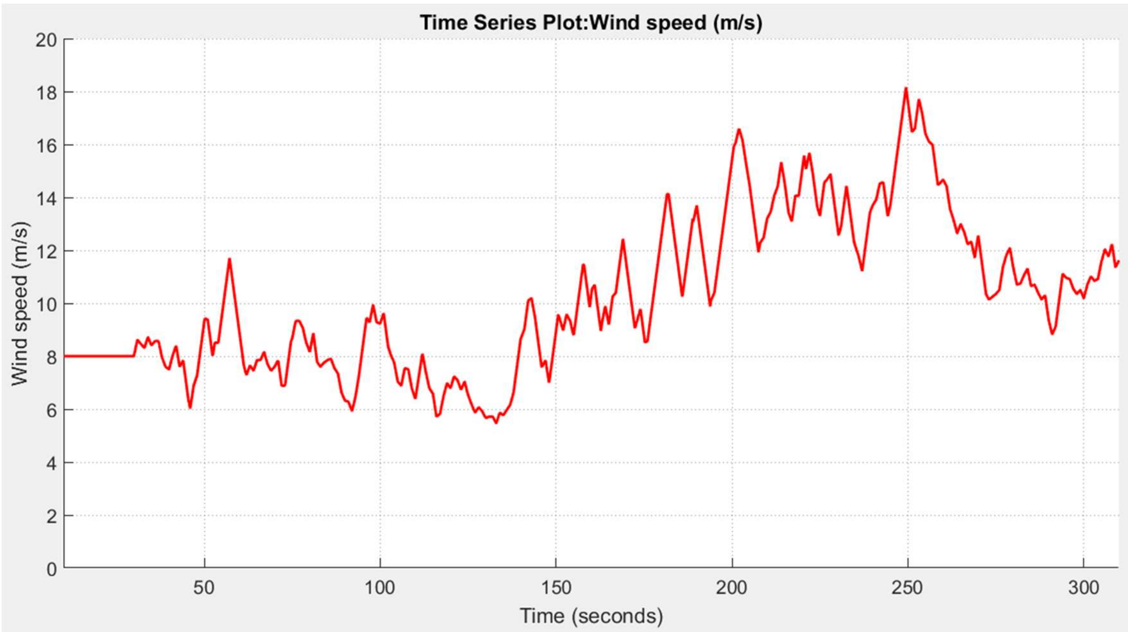

Figure 4.1 – Wind speed input for the short-term simulations on *Simulink.*

As seen in Figure 4.1, the wind input with 1-second measurements is highly variable. The maximum wind speed for this interval is 18.1 m/s and the minimum is 5.5 m/s, with an average of 10.5 m/s. Wind speeds above 9 m/s occurred 57% of the time during the simulation. The power output of wind farm without energy storage to the grid is shown in Figure 4.2.

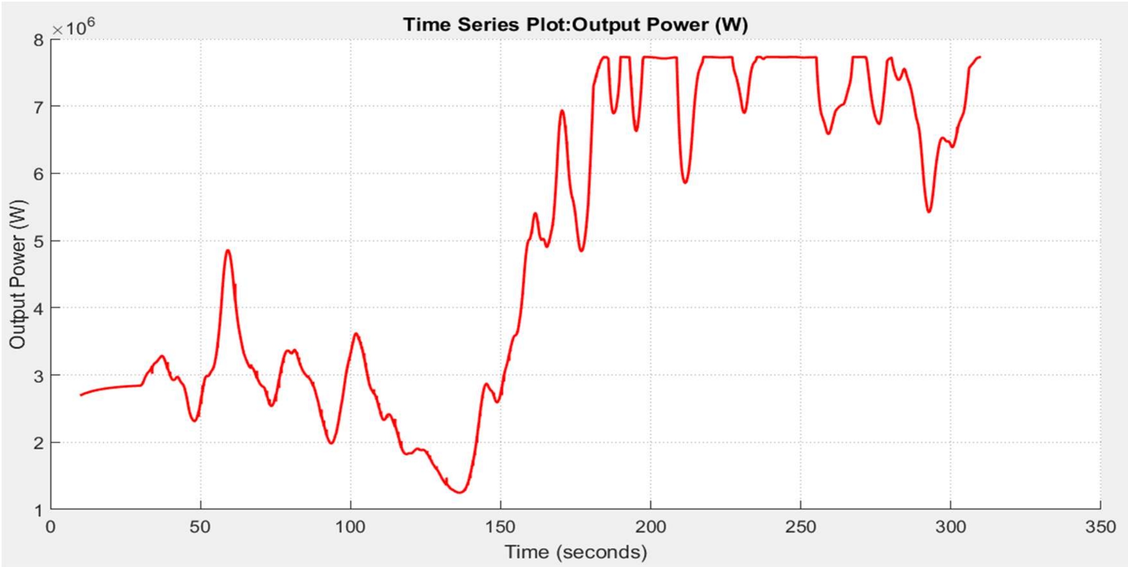

Figure 4.2 – Power output to the grid on the short-term simulation of Case 1: Wind farm without energy storage on *Simulink.*

In Figure 4.2, it is noticeable that the wind farm power output varies significantly through the 5 minutes of simulation. The largest variation goes from 1.3 MW to 6.9 MW in about 35 s. The lowest output is 1.27 MW and the maximum output is 7.73 MW, which corresponds to the nominal power output of the wind farm. Although the wind farm produces a constant output on wind speeds higher than the nominal wind speed, which occurred for 81 seconds during the simulation, these occur less frequently than periods with lower wind speed and the wind farm energy production keeps varying if the wind speed drops below the nominal speed.

It is also noticeable that the most abrupt variations of power production occur during the period just before the wind turbine reaches its nominal power. This proves the necessity of the modification of the speed control of the wind turbine, as the modifications were exactly to make this variation less abrupt, trading-off tracking the maximum power obtainable for the turbine at this region. The maximum variations that occur in this simulation are about 0.13 pu/s for the short periods that the wind turbines are coming out of nominal power output. If a less abrupt variation is desired, the speed control of the wind turbines could be further adjusted to reduce the sudden variations on a real-life turbine.

The resulting voltage on the 11 kV bus of the wind farm is shown in Figure 4.3. It is clear that the voltage level is almost constant, with variations limited to less than 0.01 pu. This result is desirable for power quality considerations of the grid and proves that the model is in stable operation. A very similar result is obtained for all simulations on this project and further plots of the voltage variation will be omitted to focus on the power output variations.

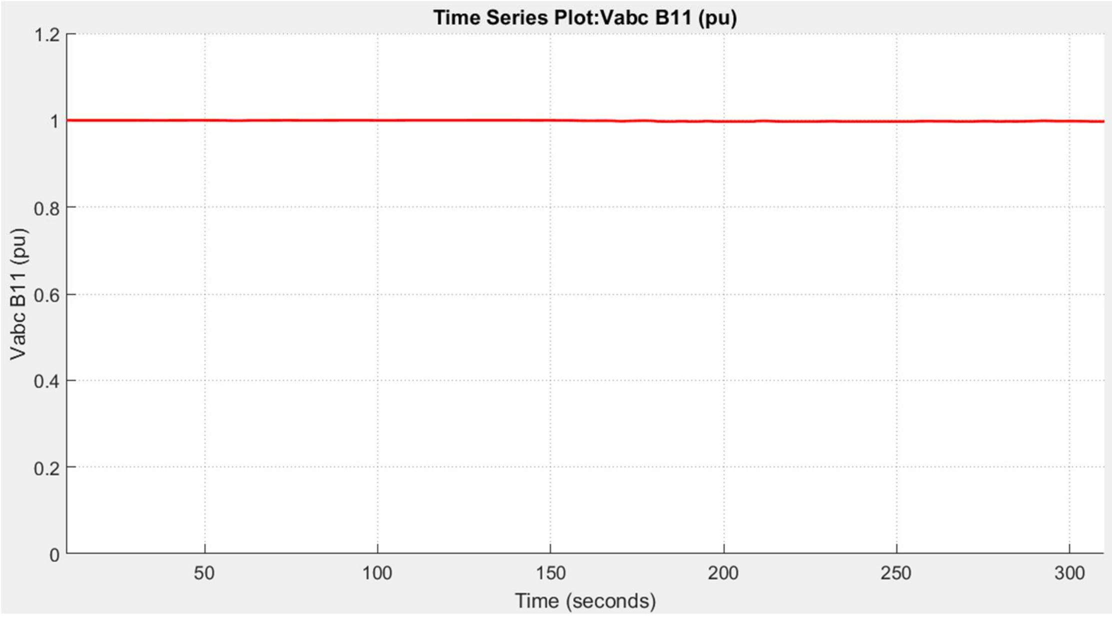

Figure 4.3 – Voltage at the 11 kV bus, in pu, on *Simulink.*

4.1.1.2. Case 2: Hybrid Wind-PHES with Storage Within the Tower

For case 2, Figure 4.4 shows the results of the operation for the wind farm generation (red solid line), hydroelectric generation (blue dashed line) and pump consumption (green dotted line). Additionally, a comparison between the actual power output (red solid line) of the system and the design power output (blue dotted line) is shown in Figure 4.5, both in pu of the design power.

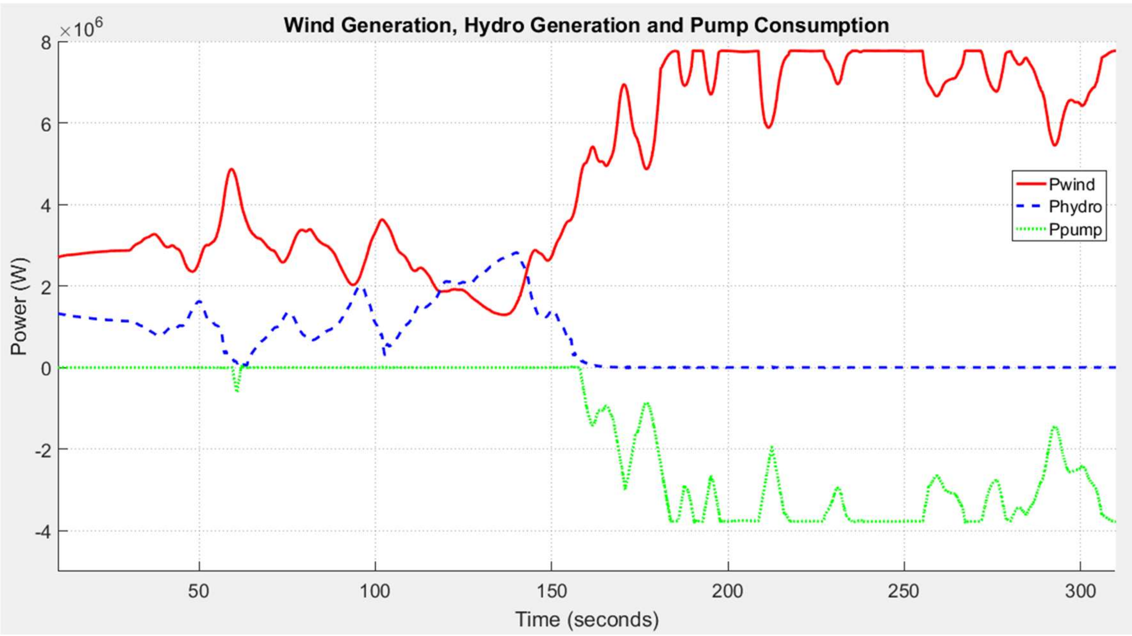

Figure 4.4 – Comparison between wind generation (red solid), hydro generation (blue dashed), pump consumption (green dotted) for case 2 of the 5-minute simulation on *Simulink.*

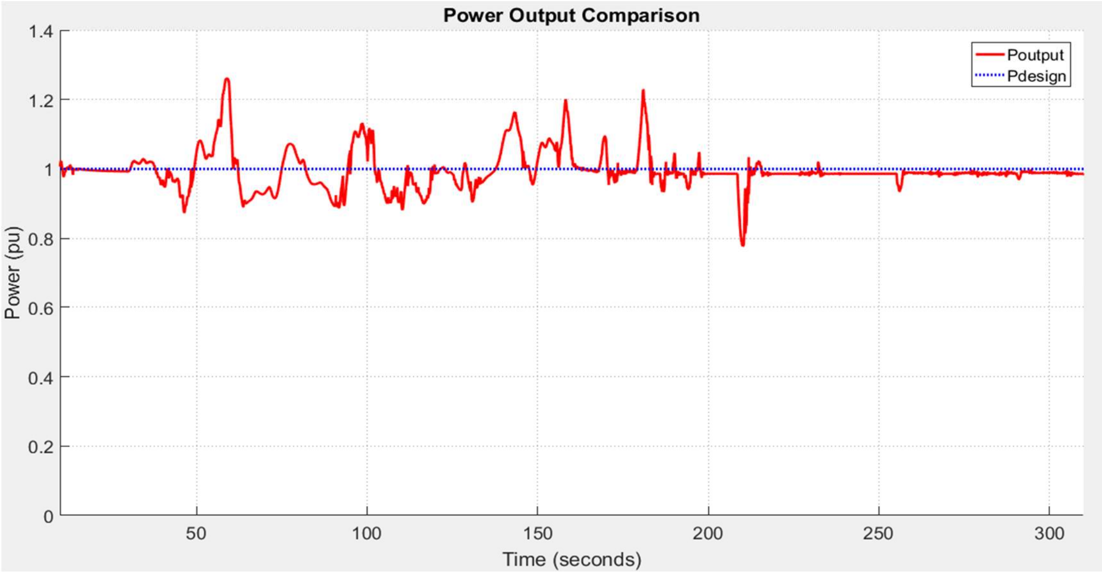

Figure 4.5 – Comparison between the actual output of the system (red solid) and the power design (blue dotted) for case 2 of the 5-minute simulation on *Simulink.*

As seen in Figure 4.4, both the hydro generation and pump consumption try to balance the wind generation, opposing its variation, to balance the power output to the design output level. Both the hydro turbine and the pump switched on 2 times from the steady state start.

From zero to 160 seconds, the wind speed is low and the hydro generation has to supply extra power for the power output to reach the design output of 4 MW. The pump also operates briefly around the 60 s mark, when the power output of the wind farm briefly surpasses the design output. From 160 seconds until the end of the simulation, the wind speed increases and there's excess power output from the wind farm, which is used by the pump to store energy. The hydro turbine operated for 47% of the time, the pump for 49% of the time and 4% of the time was spent with full wind supply and changes from pumping to hydro generation and vice-versa.

In Figure 4.5, the actual output power is being balanced around the design output at 1 pu. The governor is continuously trying to correct the response of the hydro turbine to keep up with the wind variation and therefore the output power is always varying. The pumping operation has a better response, since it is modelled to be able to correct its output faster than the hydroelectric turbine. The most prominent variations occur during the switching periods between the hydro generation and pumping, where the actual output exceeds 0.25 pu of the design power output. The imperfect response can be attributed to the imperfect dynamic control of the hydro turbine, which could be improved with more adjustment of the PID controller and the control strategy if more time was available.

The sudden variation of power output occurs exactly in the same region when the turbine tries to begin operating at nominal power and neither the turbine or the pump can react fast enough to limit the variation. However, this is unlikely to occur in a large wind farm, since the wind turbines do not experience the same wind speed at every instant, since they are located at least 300 m from each other. Even if the wind comes in a perfect perpendicular direction to the wind turbines alignment, the terrain characteristics are slightly different at every position and will change the wind speed reaching each turbine. Therefore, these types of sudden variations are unlikely to occur as fast as the simulation shows.

Normally, PHES schemes have functions related to energy management and long-term storage applications, not having particular functions of correcting power quality of the grid. Nonetheless, the short-term fluctuations in the wind speed should occur frequently and the resulting variation in the power output this could be a problem for the grid. Thus, a control strategy using a variable speed turbine and generator should provide better results and a smoother power output, as an electrical control will have a faster response to changes in the wind output.

It should also be highlighted that the variation of the power output of wind turbine already occurs naturally on wind turbines. Compared to the power curve provided by the manufacturer, the output may vary due to changes in air pressure, restrictions by the controller and yaw and pitch misalignments, as discussed by [121]. Therefore, reaching a small variation on the steady state power output is expected on a real operation scenario.

4.1.1.3. Case 3: Hybrid Wind-PHES with External Reservoir

For case 3, the system operation is almost the same of case 2 and the power output of all components are the same. The only noticeable difference is the variation of the volume of water on the storage, which is compared to case 2 on Figure 4.6. The figure shows the percentage variation of the storage volume compared to the maximum possible storage, with case 2 shown in the red solid line and case 3 with the blue dotted line and both cases starting with 50% capacity.

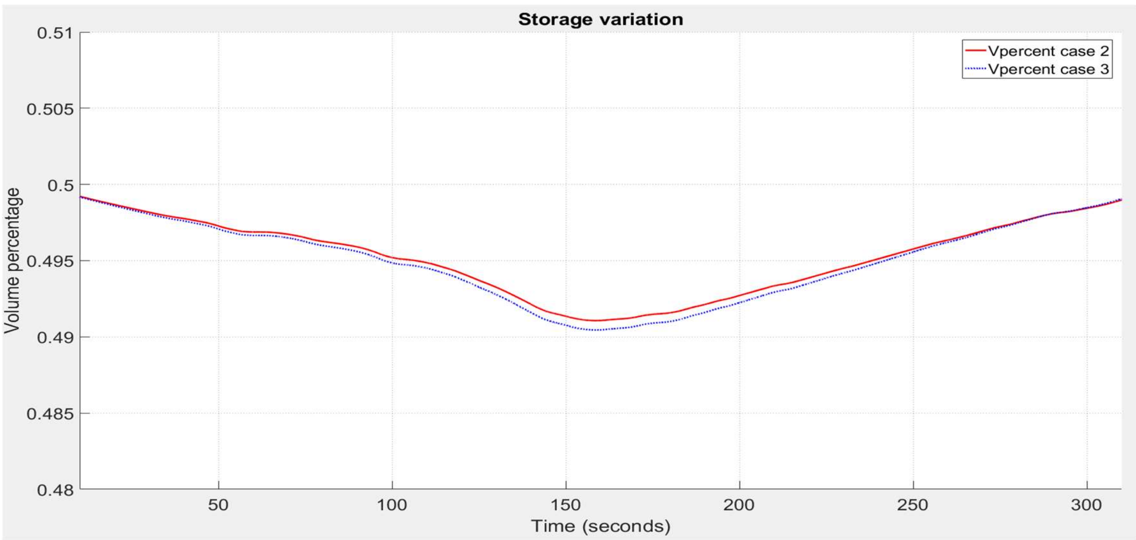

Figure 4.6 – Storage volume variation comparison of case 2 (red solid line) and case 3 (blue dotted line) for the 5-minute simulation on *Simulink.*

Since the simulation only lasts 5 minutes, the storage doesn't change much more than 1%, but the volume variation is more significant on case 3, as the nominal flow rate is higher than case 2 for both the turbine and the pump. Additionally, penstock losses for case 2 are slightly higher, which means it will marginally use more water from the reservoir over time compared to case 3. Therefore, despite the power outputs being similar for both cases, the reservoir level won't be the same and there will be a difference in the reservoir level between cases 2 and 3 for long periods of operation.

4.1.2. 12-Hour Simulation Performance

4.1.2.1. Case 1: Wind Farm Without Energy Storage

For the full 12 hours of simulated operation, the wind input to the wind farm is shown in Figure 4.7, which is the same wind input to all 12-hour simulations.

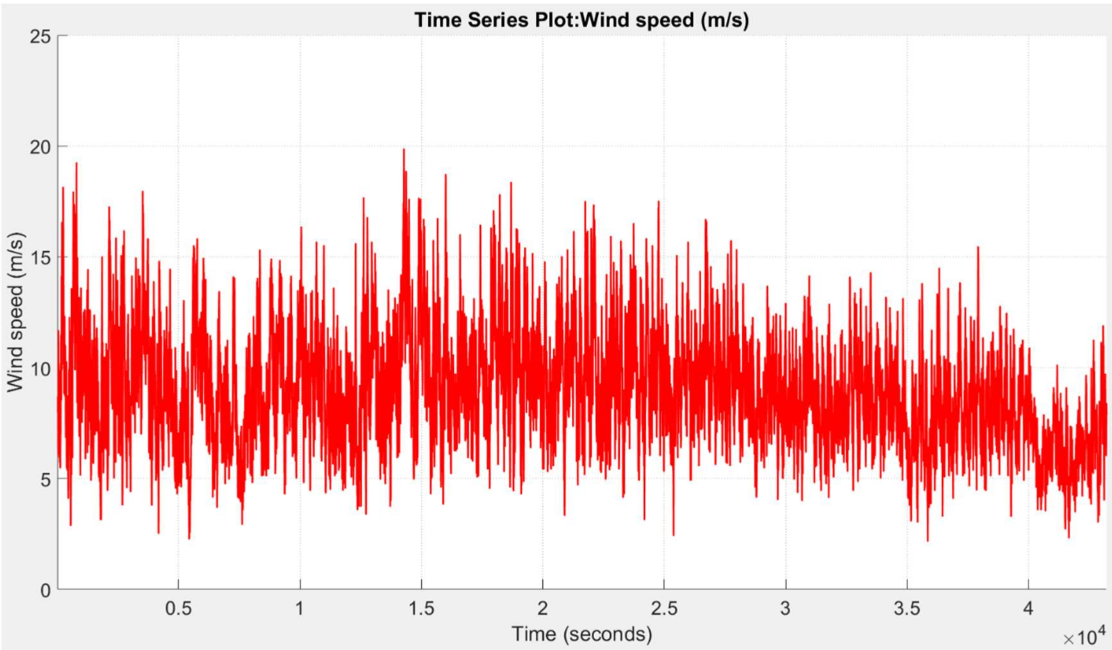

Figure 4.7 – Wind speed input for the 12-hour simulations.

As shown in Figure 4.7, the wind input is once again highly variable. As aforementioned, the minimum speed for the period is 2.15 m/s, the maximum speed is 20.27 m/s and the average speed is 9.01 m/s. The wind speed is higher than 9 m/s for 46% of the time and lower or equal 54% of the time. The power output of the wind farm without energy storage for the 12-hour simulation is shown in Figure 4.8.

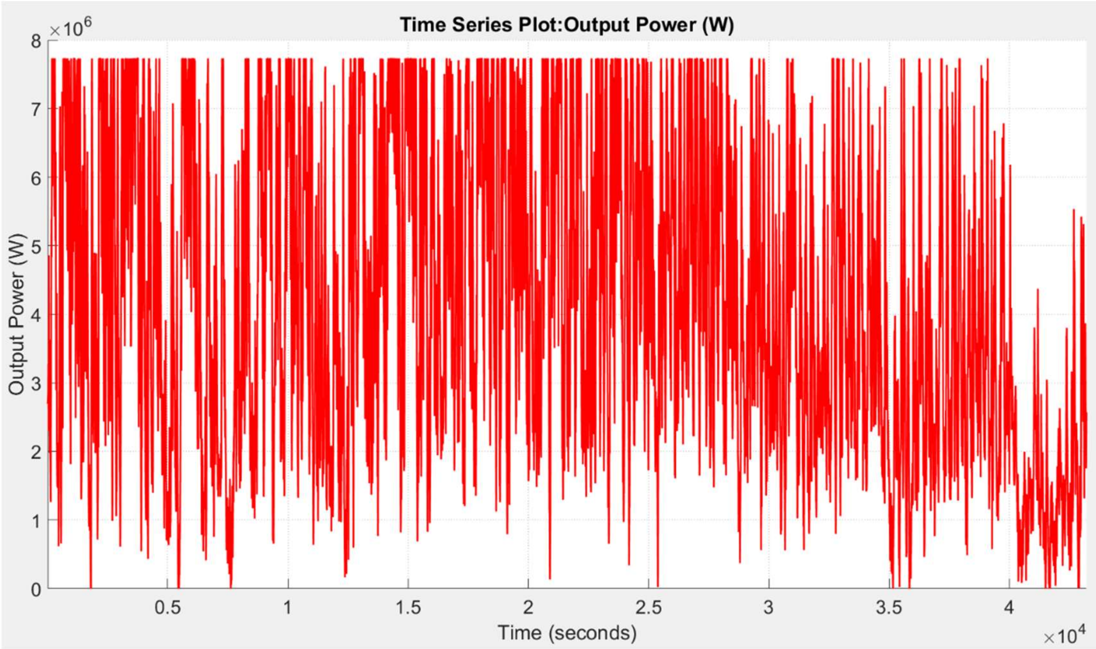

Figure 4.8 – Power output to the grid on the 12 hours simulation of case 1: Wind farm without energy storage on *Simulink.*

As seen in Figure 4.8, the wind farm produces a variable output throughout the 12-hour period. The maximum output reached is the nominal output of 7.73 MW, which happens for 13.0% of the time, or 1h 34 min, and the wind farm spent 160 seconds without producing any electricity.

Since Figure 4.8 is difficult to analyse with 43200 points, a 5-minute averaged plot of wind speed and power output is presented in Figure 4.9 and Figure 4.10, with an hour scale added in blue.

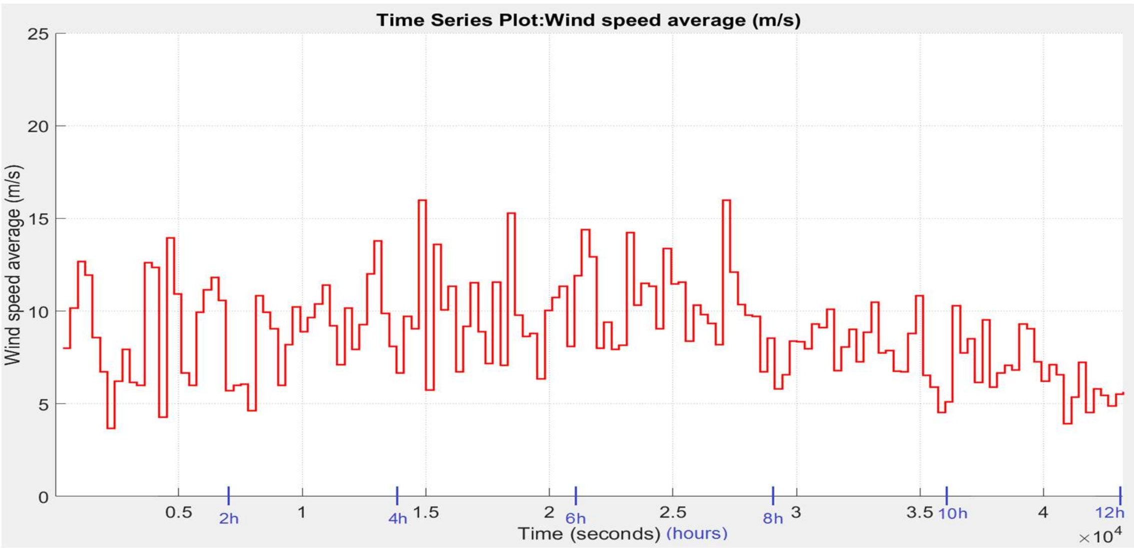

Figure 4.9 – Wind speed with 5-minute averages for the 12-hour simulation on *Simulink.*

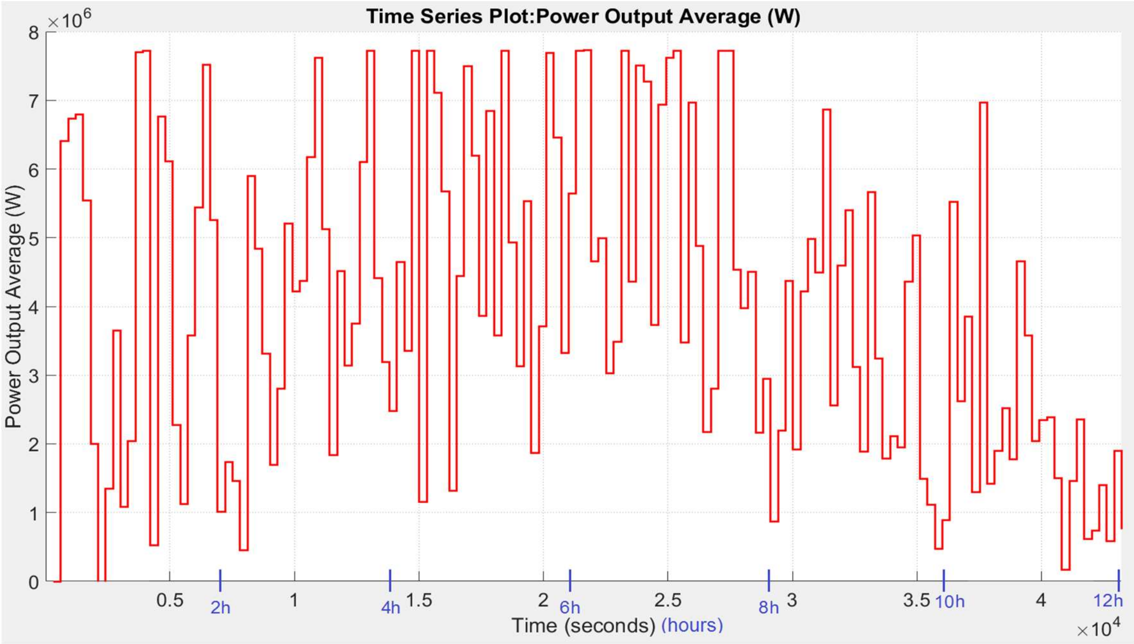

Figure 4.10 - Power output to the grid, with 5-minute averages, on the 12 hours simulation of case 1 on *Simulink.*

The figures show once again that the average wind speed and wind output are variable throughout the 12 hours of simulation, but they clarify that the average of both wind speed and power drop towards the end of the simulation. It is also possible to see that small increments on the wind speed result in considerable increases in the wind power output, as it is proportional to wind speed cubed. As these figures allow a better analysis of the behaviour of the wind turbine, the 5-minute average plots will be used for case 2 and 3 simulations.

The average output of wind generation throughout the simulation is 3.8 MW. In comparison to case 2 and 3, it would seem rather unproductive to design a PHES that will bring the average output close to 4 MW, since it is already supplying approximately this amount. However, in a real operation, wind direction would change, and the turbine would not be able to produce all the power available in the wind, as it takes time to yaw and align with the wind. Additionally, wake losses would have to be accounted, which would bring the average power down and reduce the energy production. Furthermore, the PHES scheme would help prevent stoppage time of the scheme due to grid constraints of wind generation, which would increase the average energy production in long-term.

4.1.2.2. Case 2: Hybrid Wind-PHES with Storage Within the Tower

On case 2, the results of the full 12h of simulated operation, with 5-minute averages for better visualization, are shown in Figure 4.11. The operation of the wind farm generation is represented by the red solid line, the hydroelectric generation on the blue dashed line and pump consumption on the green dotted line. The comparison between the actual power output (red solid line) of the system and the design power output (blue dotted line), with 5-minute averages, is shown in Figure 4.12. The complete responses of the 12-hour simulations for case 2, with all the 43200 points, can also be found on Appendix A.8.

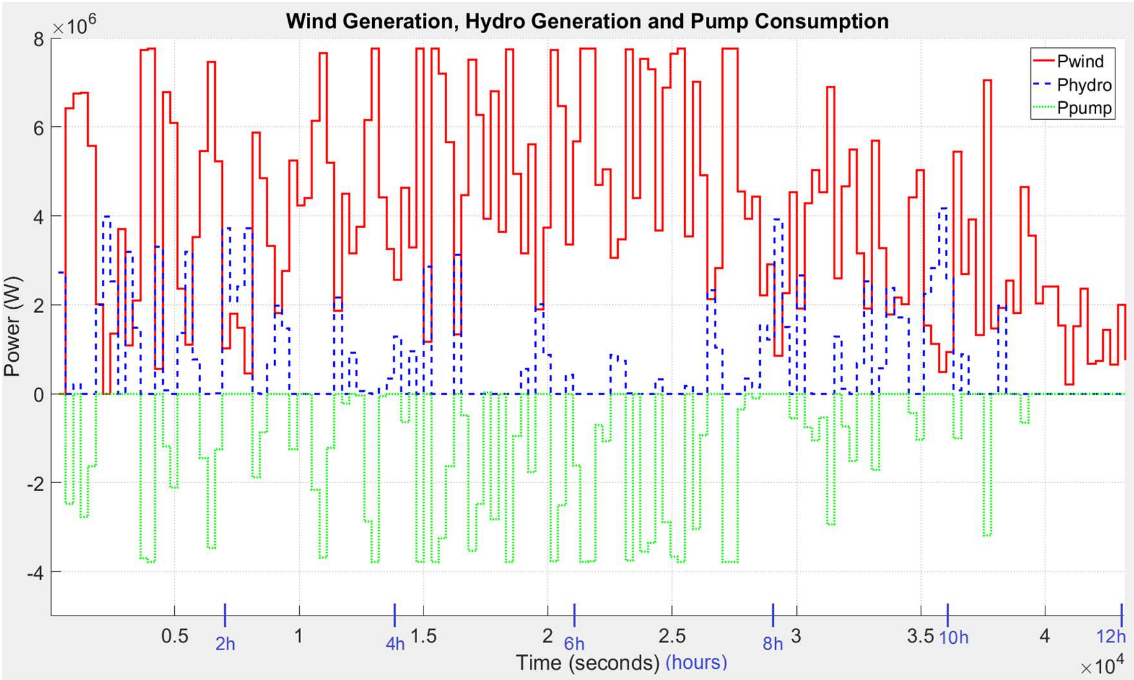

Figure 4.11 – Comparison between wind generation (red solid), hydro generation (blue dashed), pump consumption (green dotted) for the 12-hour simulations of case 2, with 5-minute averages, on *Simulink.*

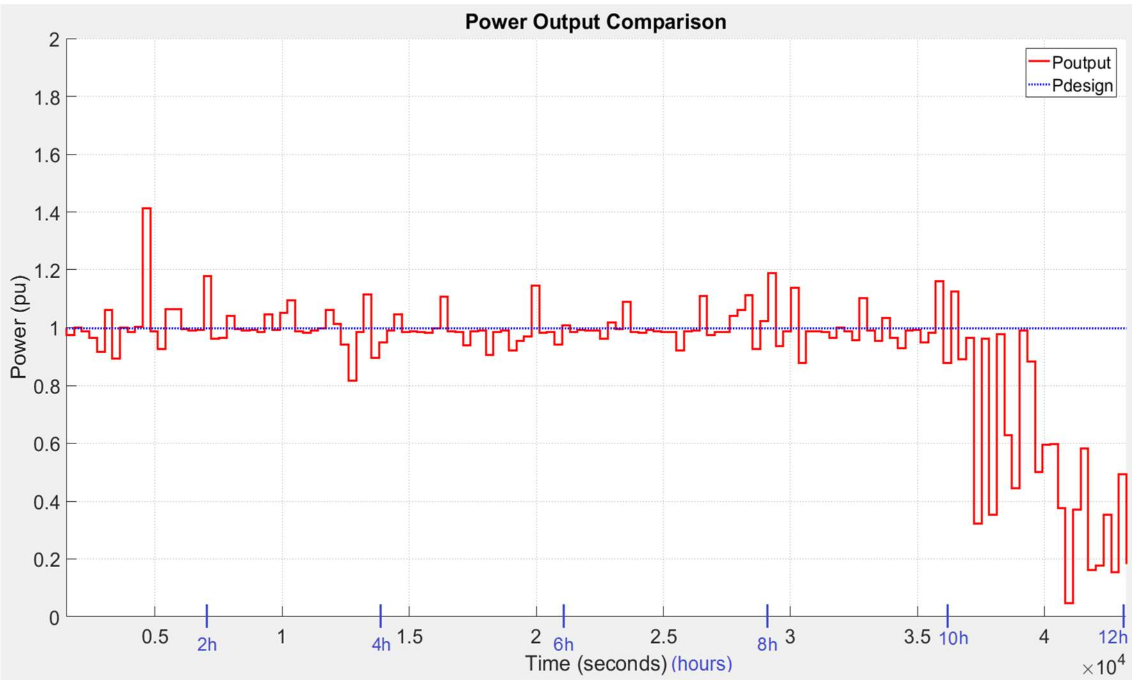

Figure 4.12 - Comparison between the power output of the system (red solid) and the design power (blue dotted) for the 12-hour simulation of case 2, with 5-minute averages, on *Simulink.*

As seen in both figures, the scheme balances the average output towards the design power output of 4 MW. Towards the end of the simulation, approximately for the last 2 hours, the reservoir empties as prolonged periods with low speeds occur. Therefore, the system only supplied the available wind power when it was below the design power. The reservoir variation is discussed along with case 3, as a comparison between both cases is made.

Table 4.1 displays the main results of the variation and average power production of the 12-hour simulation of case 2.

Average Power	
Wind generation	3.8 MW
Hydroelectric generation	0.49 MW
Pumping consumption	0.54 MW
Output to grid	3.71 MW
Output to grid before reservoir emptied	4.02 MW
Dynamic Values	
Maximum Hydro Power Output	1.13 pu
Maximum Pump Power Consumption	1.03 pu
Maximum Power Output to grid	1.79 pu
Minimum Power Output to grid	0 pu
Minimum Power Output to grid before reservoir emptied	0.58 pu
Durations and Share of the Total Simulation Time	
Duration of hydro operation	34.6%
Duration of pumping operation	41.0%
Duration of changing zone	10.3%
Duration of insufficient water for hydro operation	14.1%
Duration without any energy supply	0.14%
Duration of power output between 0.8-1.2 pu before reservoir emptied	98.0%
Duration of power output above 1.5 pu	0.2 %

Table 4.1 – Main results of the 12-hour simulation for case 2.

As shown in the Table 4.1, the results for the system were a decent performance before the reservoir emptied, with an average power output of 4.02 MW and 98% of that time the power output was balanced between 0.8-1.2 pu. However, the reservoir was emptied in the last 2 hours of operation, which indicates that the storage capacity of the system is only sufficient for hourly balances, as is discussed in Section 4.1.2.3 along with the case 3 results.

Additionally, a rather low average power is achieved for both the hydro operation and the pump operation throughout the simulation. This indicates that, for the chosen design, the machines are staying idle a long time and not using their rated capacity when required. This is a characteristic of any system that tries to balance the wind output. Unless the system is designed to transfer the wind output variation into the grid, the storage system will have to cope with the sudden variations in wind speed. The turbine was switched on 454 times and the pump switched on 468 times, which shows how challenging it is to balance the wind output to a more constant value. With more time, an improved control strategy could improve this very number of switches, delaying the shutdown and start-up of the PHES scheme when the average wind speed increases and decreases.

The full response of the system also shows that power overshoots or undershoots occur during nearly all times of switching between pumping and hydro generation and vice-versa. A maximum of 1.79 pu occurred, as high transient spikes occurred during the switches from pumping to hydro generation and vice versa. This is a rather high value that could cause problems and tripping of the protection system, even though they only occur for milliseconds. As already discussed, using variable speed technology could improve the dynamic response of the system. The other alternative would be further modifying the control of the wind turbine, so that large power variations are further suppressed during the switching between pumping and hydro generation. This could be achieved by further modification of the speed control curve, which could be done with more time available.

The energy production of the system would have to be evaluated on a full economic appraisal to test the chosen control strategy and design of the system and compared to the wind farm without energy storage and with other energy storage strategies. However, the best performance that this system design would achieve is an output of 50% if the reservoir was never emptied. Since this was shown as not being possible with the proposed storage capacity, this would have to be varied and analysed together with the full economic appraisal of the system, calculating costs and revenue until the best design is found. If enough time was available, this analysis could have been carried and, hence, this will be suggested for future studies.

4.1.2.3. Case 3: Hybrid Wind-PHES with External Reservoir

For the full 12h of simulated operation, once again, the power output results are very similar to case 2. There are slightly different operation times for the operation of the hydroelectric scheme and pumping, but these do not represent a variation greater than 1% on the variables of Table 4.1.

The comparison between the reservoir level between cases 2 and 3 is shown in Figure 4.13.

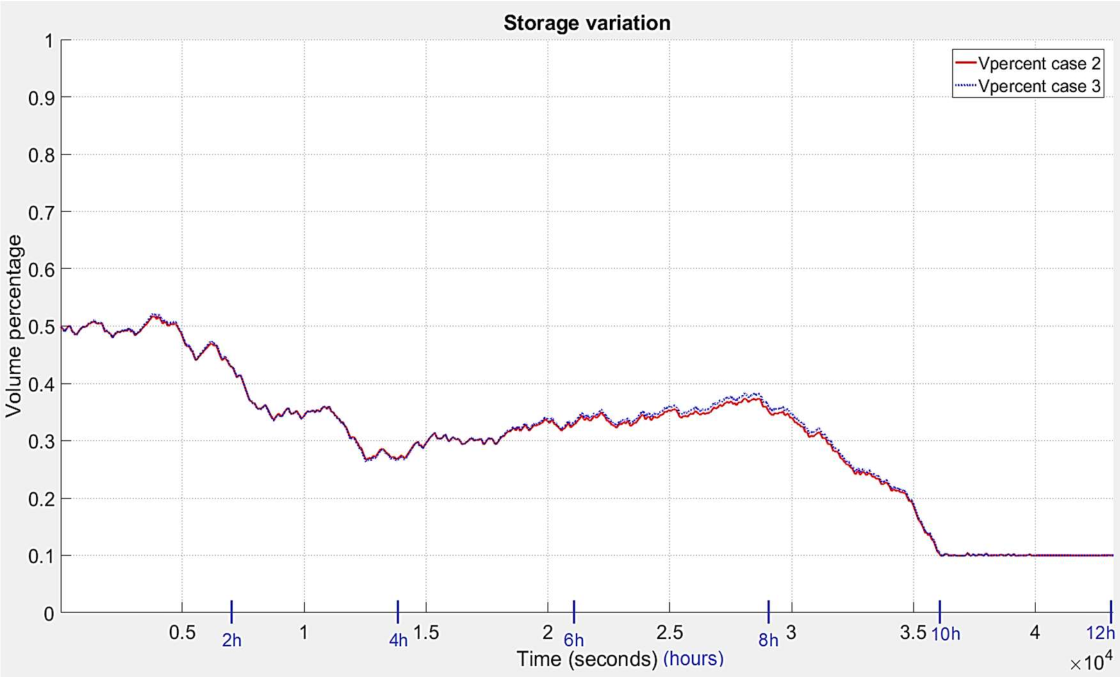

Figure 4.13 – Comparison between the storage volume of case 2 (red solid line) and case 3 (blue dashed line) for the 12-hour simulation on *Simulink.*

As Figure 4.13 shows, cases 2 and 3 have almost identical reservoir variations. However, case 2 has slightly higher losses, which makes its reservoir level become marginally lower than case 3 in the second half of the simulation. This difference resulted that the reservoir is completely empty about 1 minute later than case 2, even though the turbine flow rate is higher on case 3. On case 3, the turbine switched on 8 times more than case 2, as there was more water available before the reservoir emptied and the pumping flow rate is higher on case 3.

It can also be seen that the pumping system for the scheme would require a long period of high wind speeds to replenish the reservoir water. Since the pumping nominal flow rate is lower than the turbine, the system will struggle to fill the reservoir as fast as it is depleted. Therefore, as already mentioned before, a less ambitious target of 40-45% of the nominal power of the wind farm would produce a more balanced reservoir level variation. However, installing an extra PHES only to a produce an average output of 40-45% of the wind turbine nominal power would be hard to justify economically and would add much more complexity to the project.

Another possibility for the scheme is to extend the reservoir of the wind turbine to go higher on the tower of the wind turbine. This could allow doubling the capacity of the reservoir inside the tower and allow longer periods of low wind speeds before the reservoir is completely emptied. Nevertheless, the structural requirements for the turbine tower would be increased, since the water pressure at the base of the tower would be higher, and a more complex analysis of cyclical loads due to wind speed would be necessary. It would be a better development to increase the tower diameter rather than increase the storage height, as volume increases with diameter squared and increased water pressure at the base would be avoided. Since a complete civil analysis isn't part of the scope of the project, nor is possible within the time limits, this is a recommendation for future projects.

It is important to notice that, in this analysis, the power and control cables were considered to be passed outside the wind turbine. In a more realistic approach, it may be a better alternative to reduce the reservoir space and have the cables inside the turbine, for aesthetic reasons and possibly structural reasons as well, as the cables conduit would interfere with the tower loads. Therefore, the maximum reservoir capacity may be reduced and the maximum storage time shortened.

The lower penstock efficiency would be a characteristic of the storage inside the turbine towers, as the penstock have to be longer to connect all wind turbine towers and would probably. The greater length will also have an impact on costs, as is detailed in the next section.

4.2. Cost Analysis

Since the simulation of the operation of the system for prolonged periods of operation (eg. months, years) is not possible in practical time, the techno-economic assessment of the technology was based on the cost of the technology and a comparison to other pertinent technologies.

Therefore, the summary of the cost estimation for the 3 cases are presented as follows. This cost estimation was based on costs from other studies and should incur associated errors similar to a preliminary engineering level of precision. When necessary, the exchange ratios used were 1£ = 1.11 € = 1.32 US$ [28].

4.2.1. Case 1: Wind Farm Without Energy Storage

For a wind farm, the overall costs for projects are detailed in several studies. [122] provided the costs breakdown for case studies of 0.75 MW, 1.5 MW, 3 MW and 5 MW wind turbines, with individual formulas for each component of the turbine. A very detailed study could calculate the mass of all elements and estimate the cost of each component with these formulas. Nevertheless, since limited time is available, it was preferred to calculate the average cost per kW of all cases, do a mathematical regression to get an equation for the cost per kW of different parts of the wind turbine and apply it to the 2 MW case. The details of the regression are shown in Appendix A.7.

Since a special level of detail should be given for the tower of the wind turbine for comparison to case 2, costs were referenced from [104], which made a comparison for different tower types and materials. The tower dimensions for this the case 1 and 3 turbines are assumed to be the same as the one detailed in [104], as this is a detailed analysis of the costs of the tower. The cost of tower material, construction, transportation and lifting are assumed to be exactly the same for the wind turbines in cases 1 and 3. However, the costs of the wind turbine generator and electromechanical machinery are different for a 2 MW machine compared to the 3 MW machine presented and are estimated from [122]. Additionally, the access road, substation and grid connection costs were not part of the scope of [104], but are estimated from other references.

The summary of the results of the cost estimation for case 1 is presented in Table 4.2. The references where the values were based or estimated from are also presented.

N°	Cost description	Total	Reference
1	Tower	£ 2,677,477.48	[104]
2	Transportation	£ 273,873.87	[104]
3	Lifting	£ 154,954.95	[104]
4	Foundation	£ 57,657.66	[104]
5	Rotor	£ 1,154,827.53	[122]
6	Drive train and nacelle	£ 2,420,485.51	[122]
7	Control	£ 32,000.00	[122]
8	Access road	£ 759,000.00	[123]
9	Electric installation and substation	£ 129,729.73	[124]
10	Connection to grid	£ 785,585.59	[124]
11	Financial, Engineering and other costs	£ 562,162.16	[124]
Total		£ 9,007,754.49	-
Total Cost per kW		£ 1,125.97	-

Table 4.2 – Cost estimation for case 1: wind farm without energy storage.

As shown in Table 4.2, the total costs of the project are about 9 million pounds. This is within the range of costs found on the literature review of 900-1200 £/kW. A more detailed analysis of the terrain, foundations and grid connection could further enhance the cost analysis, as they are project specific and further analysis was limited due to time constraints.

4.2.2. Case 2: Hybrid Wind-PHES with Storage Within the Tower

For case 2, the wind turbine costs are assumed to be the same as case 1, excluding the costs related to the tower. The modified turbine tower is calculated with the same concrete price per cubic meter as case 1. It was assumed that the wall thickness at the base is 1.5 m, similar to [15, 87, 88].

To save costs with concrete, the thickness reduces linearly with height until 40 m, at the top of the reservoir, where the wall thickness is 0.5 m. Then, it also reduces with a linear relationship until the top of the turbine at 100 m, where the thickness at the top is 0.3 m. A complex structural analysis could determine a better distribution of the wall thickness of the tower, but this is the distribution assumed for the cost estimation, as limited time is available. The transportation and construction costs also consider the extra costs of concrete transportation and pouring. The cables conduit, external to the turbine, and any other adaptations required for the reservoir were assumed as having a cost equal to 10% of the cost of the tower. The PHES scheme costs were estimated from manufacturer information, price curves and books.

The summary of the cost estimation for case 2 is presented in Table 4.3.

N°	Cost description	Total	Reference
1	Wind turbine minus tower and transportation	£ 6,056,403.14	[104]
2	Tower	£ 4,662,385.57	[104]
3	Transportation	£ 796,396.40	[104]
4	Electrical cables conduit	£ 466,238.56	-
5	Pipes 900 mm SDR 26 GPS	£ 1,705,683.20	[111]
6	Penstock excavation and installation	£ 89,950.34	[123]
7	Pelton Turbine	£ 347,790.26	[125]
8	Synchronous Generator, 500 rpm	£ 200,000.00	[126]
9	Centrifugal Pump	£ 351,515.16	[127]
10	Valves	£ 60,000.00	[126]
11	Powerhouse	£ 69,639.80	[123]
12	Dump load	£ 122,951.52	[128]
13	PHES transformer	£ 90,000.00	[129]
14	HV and LV Switchgear and measuring	£ 25,000.00	[129]
15	Grid connection	£ 785,585.59	[124]
16	Financial, Engineering and other costs	£ 658,388.12	[124]
	Total	£ 16,487,657.64	-
	Total Cost per kW	£ 4,121.91	-
	Cost ratio to case 1	1.83	-

Table 4.3 – Cost estimation for case 2: wind farm with water storage inside the wind turbine tower.

As shown in Table 4.3, the total costs for the hybrid wind-PHES scheme with storage inside the wind turbine are almost 2 times more expensive than the wind farm without energy storage. The tower costs almost double in comparison to case 1, as about 4 times more concrete is used for the water reservoir inside the tower due to the increased wall thickness. The cost per kW is almost four times higher, as the output power of the scheme is 4 MW, even with an 8 MW wind farm and a 4 MW PHES scheme.

The proposed system has the objective of increasing the average energy production of the wind farm, from the typical capacity factor near 30% of wind farms in the UK to a maximum of 50% with the chosen system design and control strategy. However, since the simulations show that the storage size will not allow balancing the power output at all times, the capacity factor of the system will certainly be less than 50%, despite probably producing more energy over time. Hence, since the costs will nearly double and the project will not produce nearly double the energy output of a regular wind farm, the proposed project will probably be a worse investment than the wind farm alone.

Additionally, summing the range of costs of a wind farm and a PHES scheme found in the literature review results in a cost range of 1450-4450 £/kW, which is consistent with the value found. It is also known that the costs of the El-Hierro project amounted to 64.7 million euros (58.3 million pounds), with a larger artificial upper reservoir, two penstocks for hydroelectric plant and the pumping station, with higher length as well, and higher power ratings for all components: 11.5 MW wind farm, 11.32 MW hydroelectric plant and 6 MW pumping station [13].

4.2.3. Case 3: Hybrid Wind-PHES with External Reservoir

For case 3, the wind turbine costs are exactly the same as case 1 and most of the PHES scheme costs are exactly the same as case 2. However, penstock costs are modified, since the penstock has a shorter length, and the external reservoir costs have to be added. The excavation soil of the site was assumed as being rock to estimate the cost of digging and disposal of material. Blasting was assumed to be used at specific locations and the costs of licensing for use of explosives was included in the other costs. Table 4.4 displays the summary of the cost estimation for case 3.

N°	Cost description	Total	Reference
1	Wind turbine costs	£ 9,007,754.49	[104]
2	External reservoir excavation (rock)	£ 715,597.66	[123]
3	Blasting for excavation	£ 6,432.00	[123]
4	Disposal of material	£ 399,447.41	[123]
5	External reservoir concrete and transport	£ 621,066.53	[104]
6	Pipes 900 mm SDR 26 GPS	£ 594,744.80	[111]
7	Penstock excavation and installation	£ 26,424.17	[123]
8	Pelton Turbine	£ 347,790.26	[126]
9	Synchronous Generator, 500 rpm	£ 200,000.00	[126]
10	Centrifugal Pump	£ 351,515.16	[127]
11	Valves	£ 30,000.00	[126]
12	Powerhouse	£ 69,639.80	[123]
13	Dump load	£ 122,951.52	[128]
14	PHES transformer	£ 90,000.00	[129]
15	HV and LV Switchgear and measuring	£ 25,000.00	[129]
16	Grid connection	£ 785,585.59	[124]
17	Financial, Engineering and other costs	£ 1,012,904.80	[124]
Total		£ 14,406,584.18	-
Total Cost per kW		£ 3,601.65	-
Cost ratio to case 1		1.60	-

Table 4.4 - Cost estimation for case 3: wind farm with water storage in an artificial reservoir.

As presented in Table 4.4, this case has a total cost of 14.4 million pounds. Even with the excavation costs of a rock site and the additional costs of permits for using explosives, the artificial reservoir case is still cheaper than the water storage inside the tower. This case also has a cost per kW within the range of 1450-4450 £/kW resultant as the sum of the costs of the two separate projects found on the literature review. Considering the same amount of material and excavation of soil instead of rock would bring the costs down to 13.8 million pounds and 3,450.63 £/kW, or about 53% more expensive than the wind farm without energy storage.

4.3. Comparison and Discussion

The main costs of the three proposed cases are compared in Table 4.5. The construction costs are included in the components presented.

Comparison Point	Case 1	Case 2	Case 3
Wind turbine tower and transport costs	2.9 million pounds	5.9 million pounds	2.9 million pounds
Penstock costs	0	1.8 million pounds	0.6 million pounds
Reservoir costs	0	0 (included in tower)	2.1 million pounds
Total costs	9 million pounds	16.5 million pounds	14.4 million pounds

Table 4.5 – Comparison between the selected costs of the proposed design case studies.

The results show that, for this study, using the wind turbine towers as a water storage vessel have higher costs when compared to opening an artificial water reservoir of the same size. This is a result of the increased costs with penstock, as it is a primary cost on PHES schemes and it has to be longer to connect all wind turbine towers. Additionally, the increased costs of the wind turbine tower, which uses about 4 times more concrete than a regular tower, are still higher than constructing an artificial reservoir, even when considering excavation on rock.

Still, a complete structural analysis of the requirements and civil costs for the tower could make the total costs cheaper, as the structural analysis is not a part of the scope of this study. The increased costs of the tower are partially due to large quantities of concrete, but a significant part is due to the increased costs of transportation, equipment and the working team involved in the tower construction. If the total amount of concrete can be reduced, all related costs would be reduced and the cost gap between this technology and an artificial reservoir would be shortened. In addition, for energy storage projects, government bodies could subsidise partially or fully the project's implementation. This happens in all hybrid wind-PHES real-life schemes found in the literature review and it is justifiable for governments to invest in energy storage, as they bring increased energy supply security and stability to the grid.

The total costs for a real hybrid wind-PHES project would be site specific, as the penstock length would vary, type of soil and wind characteristics would heavily affect the project costs. Additionally, for the energy storage cases proposed, cheaper alternatives exist than the electromechanical topology used. Two-set machines, with a reversible pump-turbine, and a iterative analysis of different alternatives would save costs for the PHES scheme. The penstock pipe could also have a lower diameter, which would increase losses, but save costs. Furthermore, all costs presented are estimations and a real project would have updated prices from the industry, which could differ from the ones presented.

From the simulations, the amount of water that can be stored in the tower is able to provide balance for the hourly output of the wind farm, but is not capable of providing energy management on a daily basis or larger time scales with usual tower sizes. Increasing the tower diameter could provide more storage capacity for the system, which is a better alternative than increasing storage height due to water pressure structural concerns. If a higher diameter is used, the wall thickness can be reduced and less concrete used for the tower, reducing the associated costs.

Some advantages of the water storage within the towers can be identified over artificial reservoirs. Firstly, no flooded area is required, which is a limitation for the creation of artificial lakes, as large suitable areas or extensive excavation is required. Secondly, the height of the centre of mass of the system is lowered, which means that structural requirements of the overturning moment of the turbines could be lowered, which would impact the foundations design. Thirdly, for higher rated machines of 3-5 MW or specific terrain applications, the wind turbine towers already have higher tower diameters and wall thickness, hence the cost difference for the tower with storage would be lower. Lastly, thicker walls would lead to increasing the lifespan of the towers, which could last for more than one wind farm project, only requiring changing the electromechanical equipment on the nacelle.

Increasing the total storage with the construction of additional wind turbines is possible. However, the increased penstock costs could make this unattractive from an economic perspective. Additionally, extra head is provided by the storage within the wind turbines, as the storage height goes above ground, and the rated flow of the system can be decreased achieving the same power output. Nevertheless, this also creates additional head for the pump, decreasing the rated pumping flow for the same power output.

Disadvantages of the water storage inside the towers are the increased structural requirements due to the weight and pressure of the water, changes of the design of a standard wind turbine (cables passage, equipment repositioning), increased losses due to longer penstock, higher costs with penstock and the wind turbine tower and increased use of concrete and less environmentally friendly components, which would increase the carbon footprint of the system. Compared to a regular wind farm, the system would also have increased maintenance costs, since more sets of large mechanical machines would be operating with the added PHES scheme and replacement parts and faults would occur more frequently. Additionally, tower shadow effects would be increased with a higher tower diameter, causing more loads on the turbine blades.

The most challenging aspect of the system is the structural analysis, which could involve a complex analysis of loads on the turbine tower and foundations due to wind gusts and water pressure. However, since there is a similar project set to be tested in Germany, this technology will receive the on-site testing of its performance, but it remains to be seen how much public data will be available for the technology.

5. Conclusions and Future Works

5.1. Dissertation Summary

The study produced a *Simulink* model of a hybrid wind-PHES scheme, designed with a 8 MW wind farm and a 4 MW PHES scheme, with an objective of providing a constant design power output of 4 MW to the grid, equivalent to 50% of the rated wind farm power. Three case studies were analysed: the wind farm without energy storage, an innovative design of a water reservoir inside the wind turbine tower and a case with an artificial external water reservoir, which can hold the same capacity as the second case.

A preliminary design of the system topology was based on characteristics of the site of North Harris, as real wind speed data from the site was used for the simulations. For the wind farm, concrete towers were used, with storage up to 40 m high on the tower. The tower reservoir was sized similar to a pilot project of the same kind in Germany, considering only the tower reservoir, with a total storage capacity of 24,630 m^3 of water and 11 MWh.

The results of the simulation of the model were presented, separated in the 5-minute simulation performance and the 12-hours simulation performance. Since the model takes too much time to run the simulations, it is impossible to make a full assessment of the energy production in months or year, which limited the economic appraisal to a cost analysis of the scheme. The summary of the results is presented in the next sections.

5.2. Simulation Results

The short-term, 5-minute simulations of the model indicate that the PHES scheme is able to balance the power output of the wind farm, being able to keep the design power within the range of 0.8 pu to 1.2 pu of the design power for 98% of the time. This is a notable improvement from the wind farm operating without storage, as its output varies between 0-1 pu. However, the dynamic control of the system is not perfect and the governor control is not able to correct the power output fast enough, as constant power variation occurs. Additionally, the highest power overshoots occur during the transaction between hydroelectric generation and pumping occur.

On the 12-hour simulations, for the first 10 hours of simulation the average power is kept to 4.02 MW and the power output is balanced between 0.8 pu to 1.2 pu of the design power for 98% of the time. Nevertheless, towards the end of the simulation, the average wind speed drops for several hours and the reservoir is fully depleted towards the end of the simulation. For the full 12 hours, the scheme operates in the pumping region for 41% of the time, hydroelectric generation supply zone for 34.6% of the time, changing zone and wind farm alone operating for 10.3% of the time and insufficient water for the hydro operation happens for 14.1% of the time. Power overshoots also occur during the transaction between hydroelectric generation and pumping, even reaching over 1.5 pu approximately 0.2% of the time. Usage of variable speed generators could improve the dynamic response and reduce the overshoots of the system, as electric controls would provide a faster response than the proposed system.

Additionally, this simulations results indicate that, for the chosen strategy and reservoir size, the storage capacity is only able to provide short-term and hourly energy balancing, but daily and long-term balancing are not possible. Increasing the storage size and setting a less ambitious design power output of 40-45% of the rated wind farm power would provide a better response for the system. This design strategy is better suitable for isolated grids, which require stable output and cannot compensate fast changes in the energy supply.

5.3. Cost Analysis and Comparison

The estimates for the costs for each of the cases suggest that the water storage inside the tower of the wind turbines is more expensive than excavating an artificial reservoir of the same size, even when considering excavation of rock material. This is a result of the increased penstock length, which is a primary cost of PHES schemes, and the increased use of concrete and associated cost on the construction of the wind turbine. The total cost of the wind farm without energy storage is approximately 9 million pounds. Comparatively, the total costs for the storage inside the turbine towers case were 1.83 times higher and the total costs of the artificial external reservoir case were 1.60 times higher than the wind farm without storage.

The total cost of the tower storage case could be improved with a full analysis of the structural requirements, wall thickness and foundations of the wind turbine with water storage. As water pressure at the base increases with the storage height, increasing the reservoir diameter is a better alternative for providing more storage capacity. Higher rated wind turbines and special tower adaptors already require higher tower diameters and would decrease the gap between the water storage inside the tower and the wind farm without energy storage. The cost of both energy storage cases could also be improved by using 2 machine sets and smaller pipe diameter sizes. The latter alternative would increase losses, however.

The storage inside the tower has the advantages of avoiding the flooding and excavation of large areas for an artificial reservoir. However, the system incurs increased losses and costs with a longer penstock to connect all wind turbines, uses more concrete for the turbine tower and has a more complex structural analysis than a regular wind turbine tower.

5.4. Contribution to Knowledge

This study presented insights for the design and costs of hybrid wind and pumped hydroelectric energy storage schemes. An innovative concept of storing water inside the wind turbine towers was investigated, providing elements to analyse the overall performance and costs of the system. The information provided can be used for engineering and research applications related to the field studied.

As the concepts related to energy storage and hybrid wind-PHES schemes are relatively new, further projects can be based on the methodology and results found in this analysis, as well as in the background and literature reviewed in the elaboration of this research. Furthermore, the software model produced for this study on *Simulink* can be adapted and used for similar applications and studies in future projects.

5.5. Suggestions for Improvements and Future Projects

Future projects could look into the structural analysis and requirements of integrating water storage inside the wind turbine, which could not be detailed due to time constraints. An interesting analysis could be to vary the storage size with the tower diameter as well as the tower height and detail the structural requirements and cost implications. To reduce the total costs of the system, the PHES scheme could be designed considering multiple topologies and layouts, which were fixated on this study for comparison between cases. Specific types of concrete and other materials may be compared to save costs as well. Additionally, a sensitivity analysis of the design power output of the system could provide the best strategy for balancing the energy output of the wind farm and the reservoir level.

Another development would be to gather wind data over a longer period of measurements and assess the energy production and full economic analysis of the project of the system. Other studies could focus on applications of the hybrid wind-PHES system with storage inside the wind turbine tower for other particular sites. Underground water reservoirs may be used as natural lower reservoirs with turbine towers used as the upper reservoir. Offshore application could also be analysed, with an economic assessment of short-time storage, a variable speed turbogenerator and the additional constraint of increased corrosion.

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Appendices

A.1 Instructions for Running the *Simulink* Model With Default Parameters

The basic steps to run the *Simulink* model with default settings are listed below. The same instructions are listed in the file "Instuctions.txt".

1. Confirm that the *Excel* file "Windinput.xlsx" is on the same folder as the model "windPHES_final.slx" and adapted to the layout presented in Appendix A.2.
2. Open the file: "windPHES_final.slx";
3. Run the model (by pressing Ctrl+T or clicking the green "Run" button);
4. Double click the "Measurements" block;
5. Analyse the results double clicking the desired "Scope" blocks.

The default settings are the same simulation settings for the short-term simulation of case 2. The initial storage is equivalent to 50% of the maximum capacity and the simulation time is 310 seconds, equivalent to 5 minutes of simulation after 10 second of constant wind speed to reach steady state.

All the parameters can be modified within *Simulink* to adequate the model for a particular case study. Changing of specific parameters have to be adjusted on the desired block of the specific component, generally by double clicking the component and editing the fields. However, any user should have a basic level of knowledge in *Simulink* modelling and power systems for modifying the model. The "help" command in *MATLAB* provides additional support for all blocks.

A.2 Instructions for Formatting the Wind Speed *Excel* File Input

The *Excel* file “Windinput.xlsx” needs to be formatted before simulating the model, as shown in Figure A.2.1. The correct layout uses the first row of the document as the name of the variables used in each column. From the second row, the values of the variables are entered and can be altered as needed. The first column is required to always be time points. The second row is used here to set the wind speed values to each second, with linear variation between each point, as set in the “From Spreadsheet” block. The default file is already formatted to the correct layout. A similar description is also listed in the help section of the “From Spreadsheet” block.

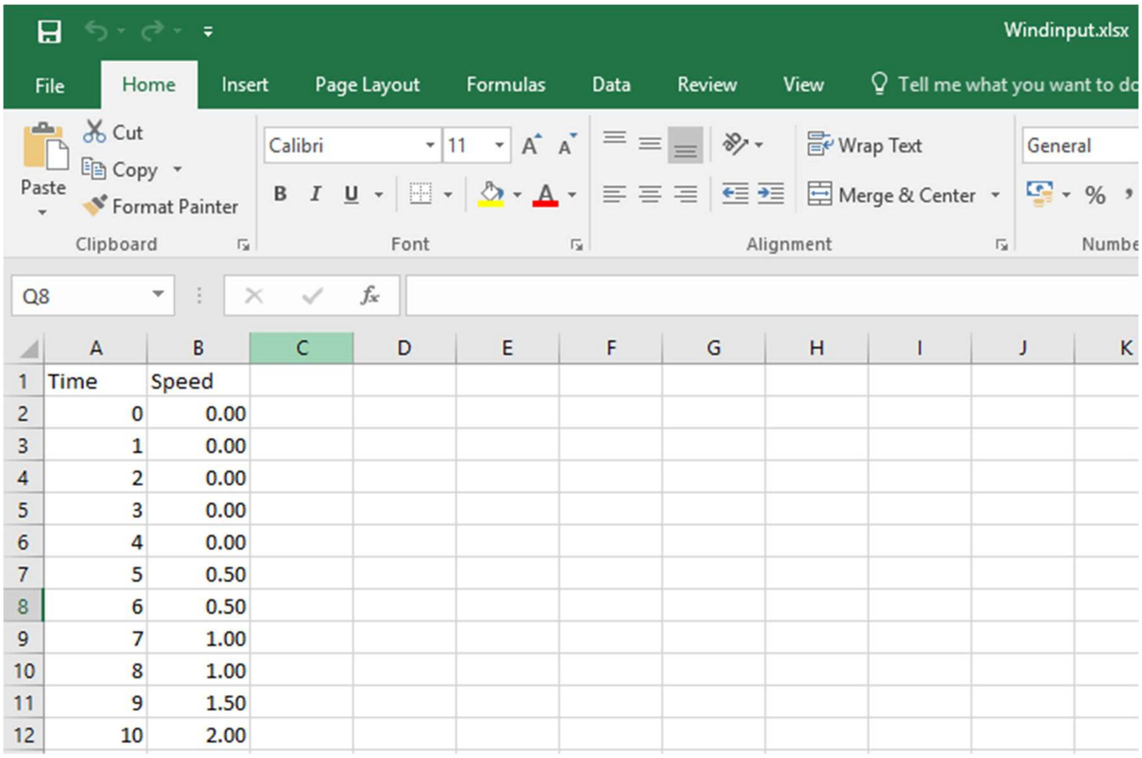


Figure A.2.1 – Correct formatting of the *Excel* file “Windinput.xlsx”.

A.3 Wind Data Analysis

The 6 months of wind data from North Harris, measured with 1 second intervals, yielded 11.7 million data points. To check the accuracy of wind data, all data was plotted and briefly analysed to check for any prolonged periods without measurements or sharp variations. Since the data was previously filtered, no correction was made on the data provided by [95]. Figure A.3.1 displays the wind speed graph over a random day at the site.

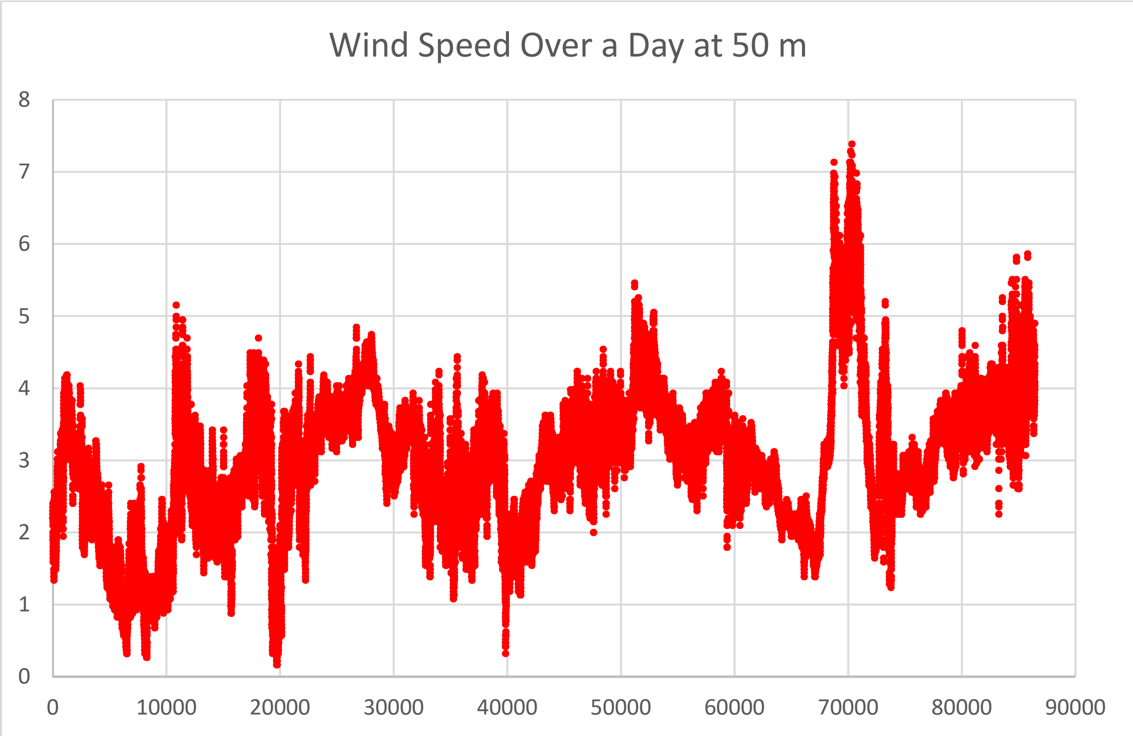


Figure A.3.1 – Wind speed over a random day at 50 m at the North Harris site [95].

It is clearly visible that the wind speed varies considerably over the day and, consequently, the wind turbines production will vary significantly. From the data, the averages for wind speed and temperature were 8.69 m/s and 5.1°C.

With the average wind speed at 50 m, the Rayleigh distribution was used to estimate the probability of occurrence of a certain wind speed at the North Harris site. The comparison between the distribution and the actual wind speed occurrences are shown in Figure A.3.2.

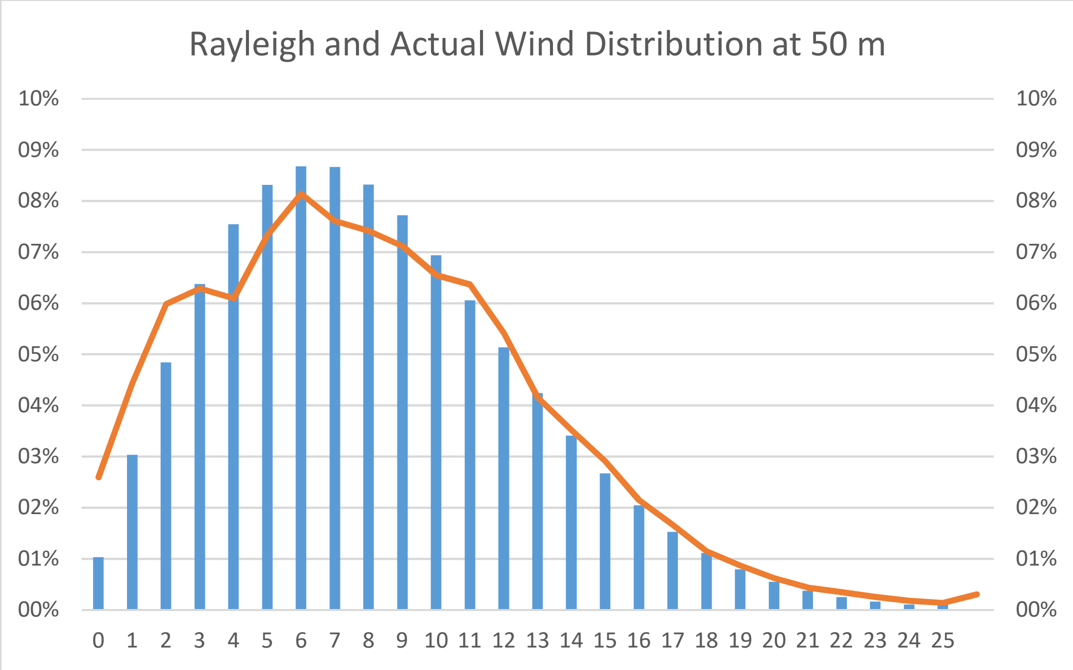


Figure A.3.2 – Comparison between the actual wind distribution (orange line) and the Rayleigh distribution (blue bars) at 50 m height.

Analysing the figure, it can be concluded that the Rayleigh distribution is not a perfect fit for the wind characteristics at that site and a Weibull distribution with a different value of the shape parameter k would provide better results. However, due to time constraints, it was preferred to use the Rayleigh distribution as a first approach to the wind characteristics of that site.

The wind direction was divided in 8 different sectors of 45° and the occurrence on each sector at 50 m is plotted on Figure A.3.3. It is clearly visible that the South and Southwest sectors have a higher occurrence of wind, each occurring about 17-18% of the time, with a significant occurrence on the East direction as well. Figure A.3.4 also shows the average speed for each sector at 50 m, being that the higher average wind speed occurs at the South and Southwest sectors and concluding that this is the preferential wind direction.

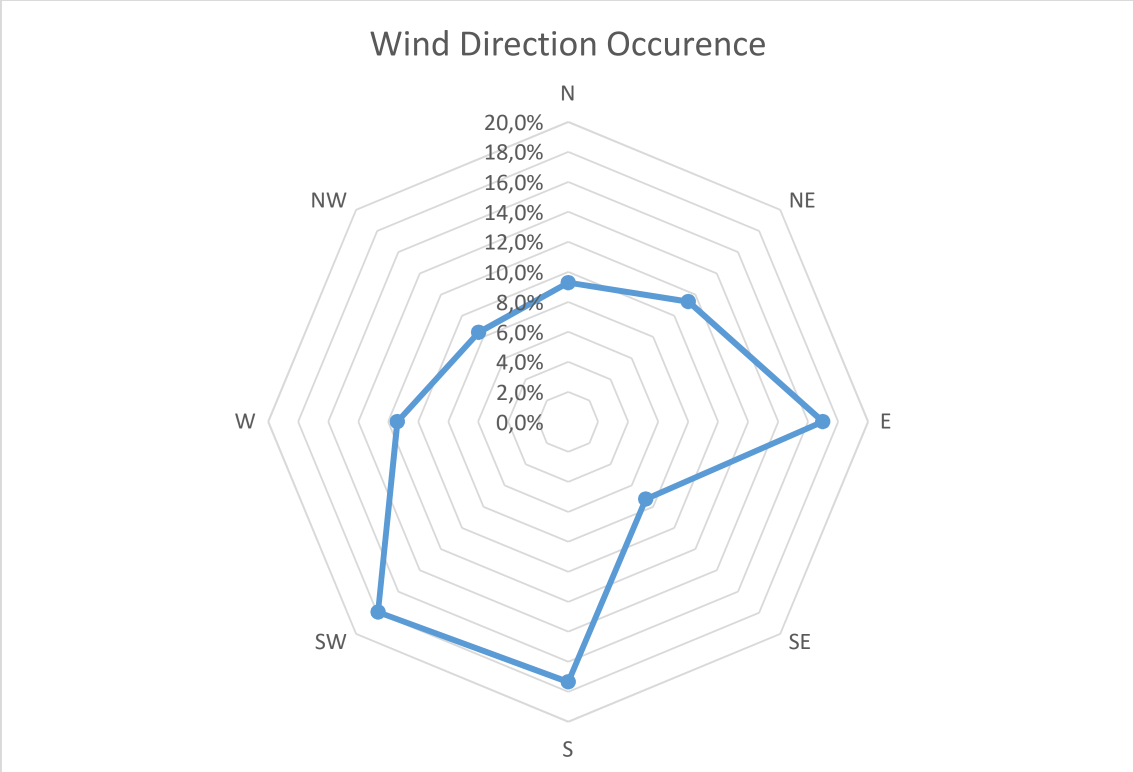


Figure A.3.3 – Distribution of occurrence of direction of wind at 50 m at the North Harris site.

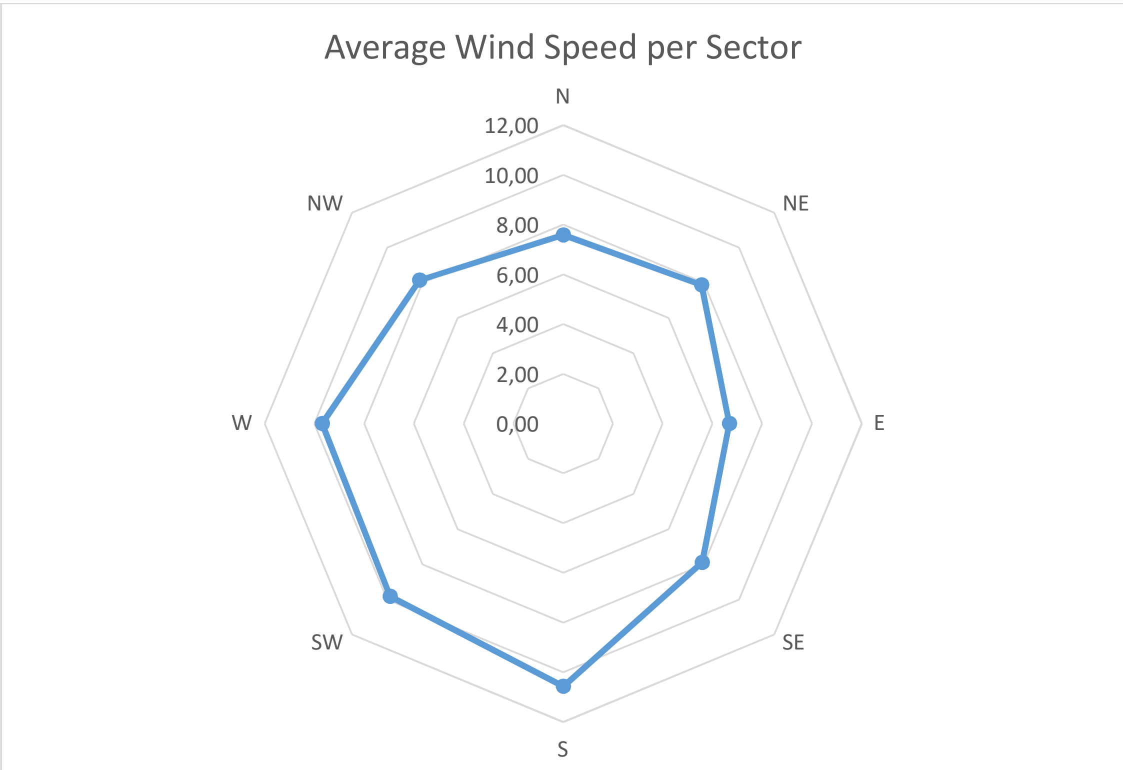


Figure A.3.4 – Average wind speed per sector at 50 m the North Harris site.

To correct the average wind speed to 100 m, the power law was used, as expressed by Equation 2.1. A typical surface roughness of 0.1 m was used, suitable for a site with a few constructions or trees nearby [17, 19]. The new average wind speed resulted in 9.66 m/s and the new Rayleigh distribution at 100 m is shown in Figure A.3.5.

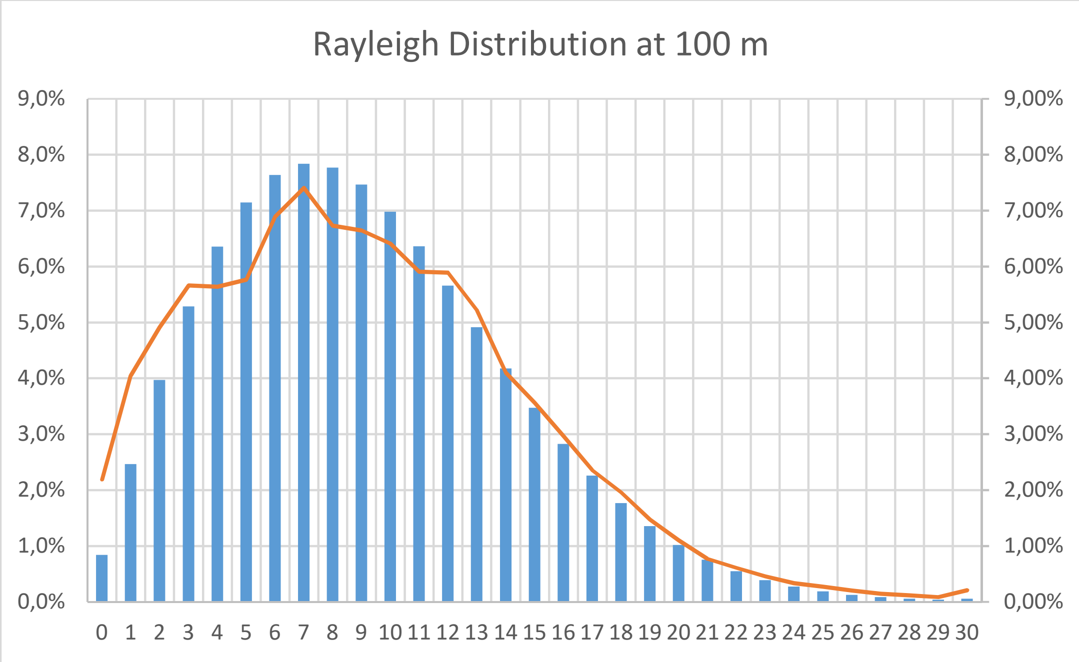


Figure A.3.5 - Comparison between the actual wind distribution (orange line) and the Rayleigh distribution (blue bars) at 100 m height.

Once again, the Rayleigh distribution is not a perfect fit for the wind distribution, but it was preferred to use the Rayleigh distribution as a first approach to the wind characteristics of that site. With this distribution at 100 m, an estimative for the probability of exceedance for each wind speed can found, which is used to design the PHES system, as explained in Chapter 3.

A.4 Wind Turbine Power Curve

The power curve for the wind turbine can be altered within the respective wind turbine block on *Simulink*. The simulated turbine, equivalent to the one simulated by [100, 101], has a power curve described by Table A.4.1.

U (m/s)	P (kW)
0	*0*
1	*0*
2	*0*
3	*0*
4	*46*
5	*160*
6	*302*
7	*482*
8	*722*
9	*1020*
10	*1416*
11	*1884*
12	*1941*
13	*1941*
14	*1941*
15	*1941*
16	*1941*
17	*1941*
18	*1941*
19	*1941*
20	*1941*
21	*1941*
22	*1941*
23	*1941*
24	*1941*
25	*1941*
26	*1941*
27	*1941*

Table A.4.1 – Relationship between wind speed and output power for each wind turbine.

For this turbine, the cut-in speed for the turbine is 3.5 m/s. An important parameter for the design is the wind speed which the output of the wind farm is 4 MW, which is approximately 9 m/s. Nominal power is reached at 12 m/s and the cut-out speed is approximately 27 m/s. The cut-out speed can be altered by changing the maximum pitch angle, which was set at 30° for this analysis. The power curve graph of each wind turbine is shown in Figure A.4.1.

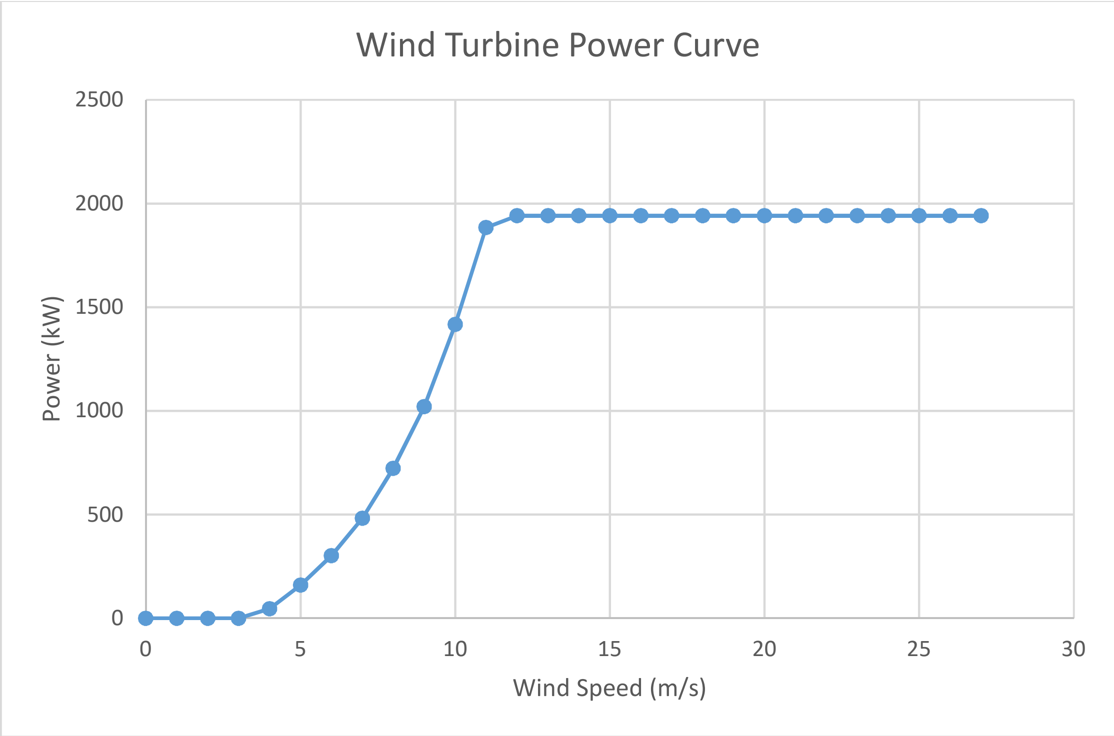


Figure A.4.1 – Wind turbine power curve.

A.5 Penstock Losses Calculation

The type of pipe decided for the project is the HDPE SDR 26 900, from [111]. The pipe external diameter is 1 m, with a wall thickness of 0.035 m and an internal diameter of 0.830 m. The mean velocity of the water in the pipe is given by Eqaution A.5.1, from [43].

$$\bar{U}_{water} = \frac{4Q}{\pi d^2} \qquad \text{(Eq. A.5.1)}$$

For the chosen pipe, the speed for the three different storage height cases are 4.07 m/s, 4.88 m/s, for cases 2 and 3 respectively. The Reynolds number for the flow is also given by Equation A.5.2, from [43]. Water characteristics at 5°C of $\rho = 1000\ kg/m^3$ and $\mu = 1.51x10^{-3}\ Pa.s$, from [130], were used. The result for the flow of the two cases is 2.24x10^6 and 2.69x10^6.

$$Re = \frac{\rho \bar{U}_{water} d}{\mu} \qquad \text{(Eq. A.5.2)}$$

The total losses in the pipe are given by sum of friction losses plus turbulence losses. The former are given by Equation A.5.3 and the latter by Equation A.5.4, both adapted from [43]. The friction factor is found on Figure A.5.1, from [43]. The coefficient K is given by the sum of all turbulence loss factors through the pipe.

$$H_{L,f} = \frac{\phi L U_{water}^2}{2gd} \qquad \text{(Eq. A.5.3)}$$

$$H_{L,t} = \frac{U_{water}^2}{2g} K \qquad \text{(Eq. A.5.4)}$$

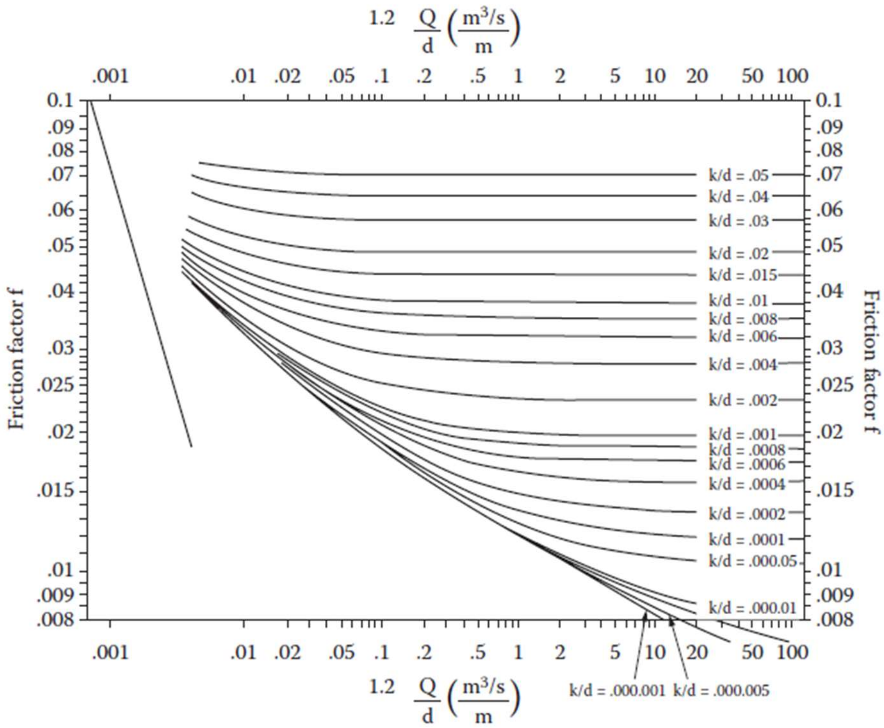


Figure A.5.1 – Moody chart, from [43].

Therefore, for a penstock lengths of 1,52 km and 0.53 km and a pipe roughness of 0.05 from [131] and a friction coefficient of approximately 0.012 from the Moody chart, Table A.5.1 presents the losses for the chosen pipe. For the turbulence losses, the coefficient K is estimated at 1.9 for case 2, accounting for 4 pipe entrances and 3 sudden expansions and 0.1 for case 3, with only 1 pipe entrance.

Head Losses	Case 2: storage inside tower	Case 3: external reservoir
Friction Loss	18.6 m	9.3 m
Turbulence Loss	1.6 m	0.1 m
Total Loss	20.2 m	9.4 m
Percentage of Gross Head Lost	8.4%	4.7%

Table A.5.1 – Estimated losses for the selected pipe.

A.6 Efficiency Curve for the Turbine

The efficiency curve used for the Pelton turbine in this project was a result of a mathematical regression of real efficiency points of a Pelton 2-Jet turbine, provided by [112, 113]. Since no points were available at a flow ratio below 30%, it was assumed that the turbine starts operation at a flow ratio of 10% at approximately 50% efficiency and achieves 75% efficiency at flow ratio of 20% and these points were used on the regression as well.

A comparison between the efficiency curve used and the efficiency points provided by [113] is shown in Figure A.6.1.

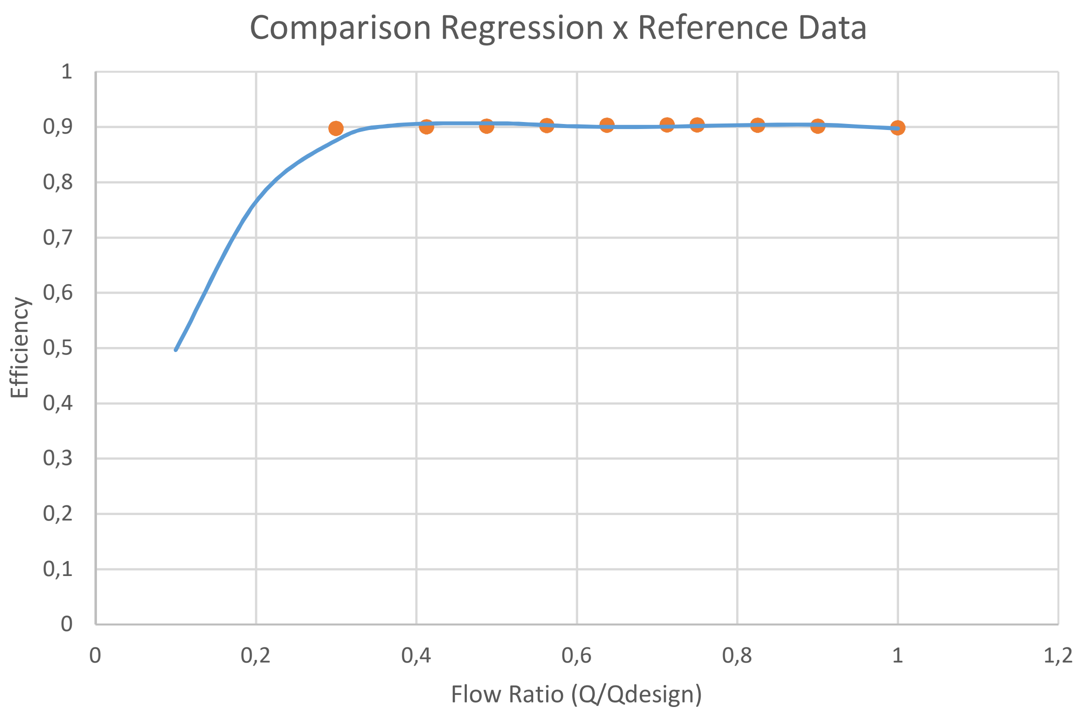


Figure A.6.1 - Comparison between the efficiency curve used for the model and the efficiency points for the Pelton turbine from [113].

As seen in both the table and the figure, the part load efficiency is very high and doesn't vary much from 90%, which is a particular characteristic of Pelton turbines [58].

The efficiency curve and its coefficients used in the *Simulink* model are shown in Equation A.6.1 and Table A.6.1, being $x = \frac{Q}{Qnominal}$, the ratio between the actual flow and the nominal turbine flow. The range of efficiencies and its variation with the flow ratio are also shown in Table A.6.2.

$$\eta_{turbine} = a_1x^5 + a_2x^4 + a_3x^3 + a_4x^2 + a_5x + a_6 \qquad (\text{Eq. A.6.1})$$

a_1	a_2	a_3	a_4	a_5	a_6
4.811347521	-18.9259027	28.5964037	-20.7059797	7.16062537	-0.03913904

Table A.6.1 - Coefficients for Equation A.6.1.

Flow Ratio (Q/Qnominal)	Efficiency
0.1	0.497
0.2	0.765
0.30	0.876
0.37	0.903
0.50	0.907
0.60	0.901
0.70	0.900
0.80	0.903
0.90	0.904
1.00	0.897

Table A.6.2 - Efficiency relationship used for the with the flow ratio used on the model.

A.7 Costs Regression for the Wind Turbine

The detailed costs for the wind turbine are detailed by [122], with each component's cost estimated with formulas based mostly on its mass or its rating. The study also presented total costs for case studies of turbines with 0.75 MW, 1.5 MW, 3 MW and 5 MW.

Since limited time is available, a mathematical regression with the total costs for the pertinent areas was carried to estimate the costs for the rotor, drive train and nacelle, control system and safety. The costs for those sections of the wind turbine of all the baseline design cases of [122] are summarized in Table A.7.1.

Power	0.75 MW	1.5 MW	3 MW	5 MW
Rotor costs	£ 102,926.26	£ 125,015.15	£ 183,820.96	£ 224,913.03
Drive train and nacelle costs	£ 258,213.13	£ 284,228.79	£ 323,737.88	£ 374,887.88

Table A.7.1 – Costs per MW for the rotor and drive train/nacelle of the design cases from [122].

For the mathematical regression, these points are used to create an extrapolation curve to estimate the costs at any power rating. The comparison between the costs per kW for the rotor and drive train/nacelle from [122] and the mathematical regression are shown in Figure A.7.1. The control system costs are assumed to be 8,000 £/MW, as it is very similar for all cases on [122]. The exchange ratio used was 1.32 US$/£ [28].

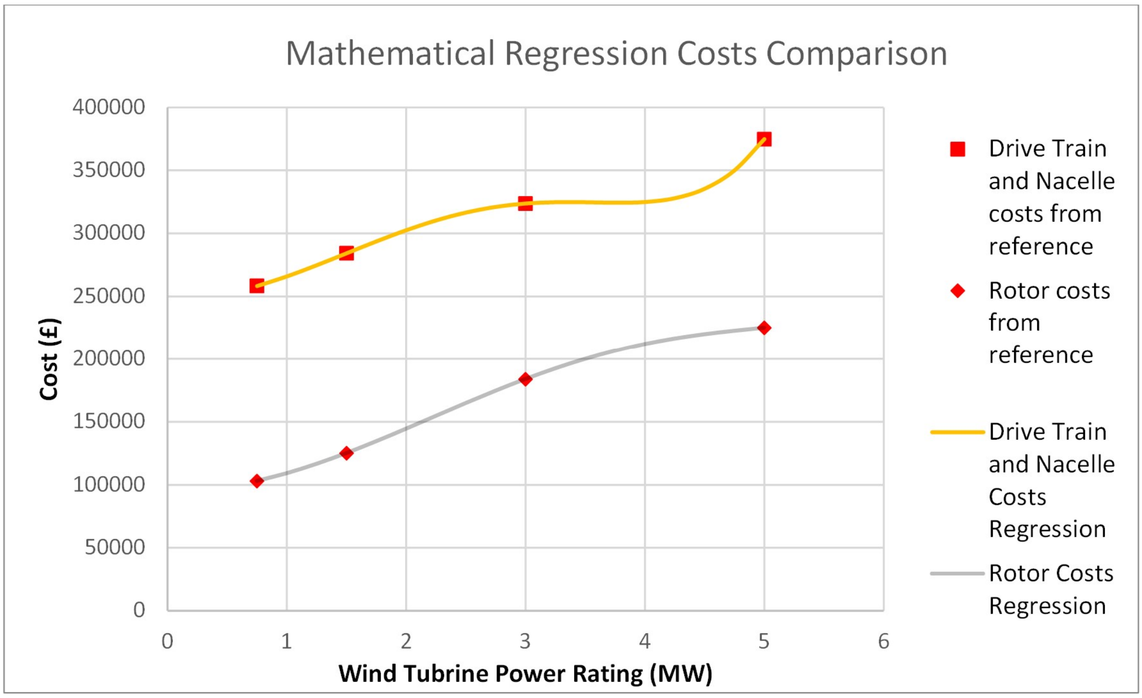


Figure A.7.1 – Comparison between the mathematical regression costs and the costs from [122].

As seen on the figure, the mathematical regression provides a reasonable approximation for the costs of both rotor and drive train equipment. The cost curve used is described by Equation A.7.1, with being $x = P_{ele,wind}$ in MW. The coefficients for the equation for the rotor costs are presented in Table A.7.2 and for the drive train costs are shown in Table A.7.3.

$$W = a_1x^5 + a_2x^4 + a_3x^3 + a_4x^2 + a_5x + a_6 \qquad \text{(Eq. A.7.1)}$$

a_1	a_2	a_3	a_4	a_5	a_6
89.88237393	-843.917888	0	15071.40002	0	94694.2915

Table A.7.2 - Coefficients for the rotor costs on Equation A.7.1.

a_1	a_2	a_3	a_4	a_5	a_6
367.3077	-2461.88	0	20739.49	0	247239

Table A.7.3 - Coefficients for the drive train and nacelle costs on Equation A.7.1.

A.8 Complete Results of the 12-Hour Simulations for Case 2

The complete plots of the 12-hour simulations for case 2 are shown in Figure A.8.1 and Figure A.8.2. These were not use in the main text, since it is hard to visualize trends with 43200 points.

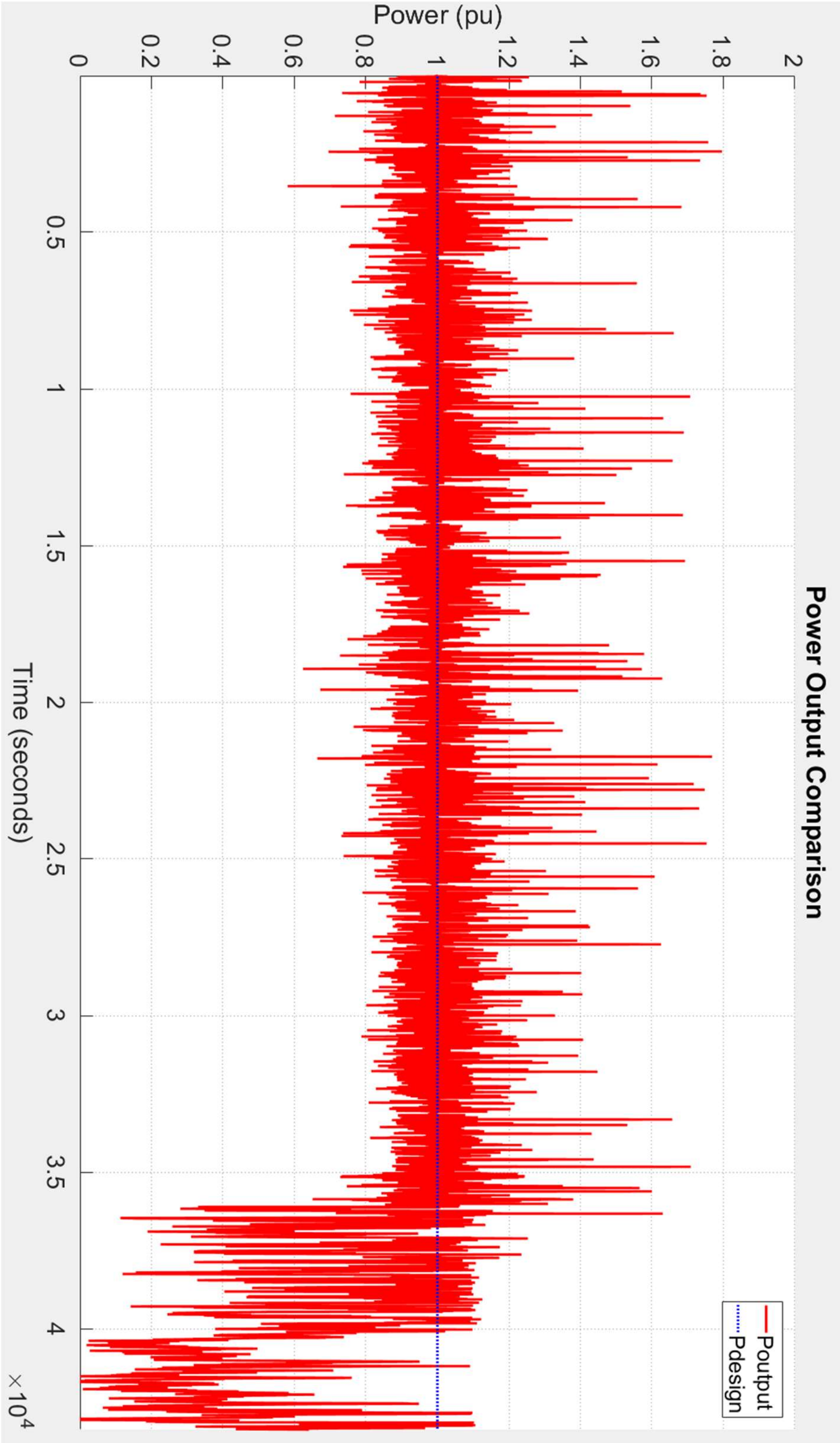


Figure A.8.1 - Complete 12-hour simulation results for the comparison between the power output and the design power for case 2, on *Simulink.*

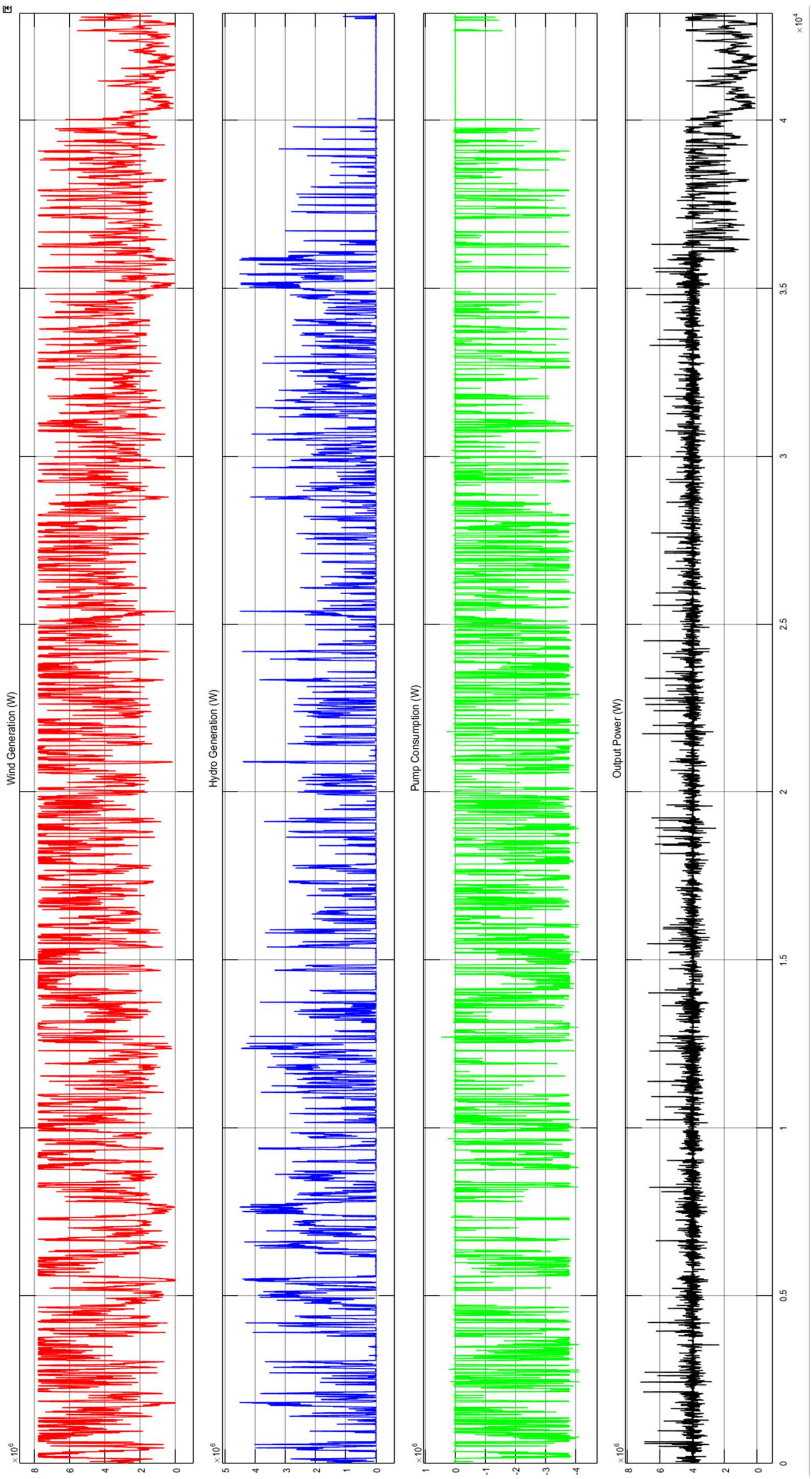


Figure A.8.2 – Complete 12-hour simulation results for the wind generation, hydro generation and pump consumption for case 2, on *Simulink.*

A.9 Risk Assessment Form

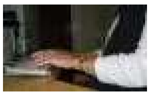
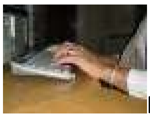
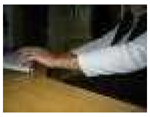
Record of Assessment

Workstation location: (School, Division, Unit etc., building, room no & floor)	*Ratcliffe Terrace 63 Room 4, Main Library Floor 4*
Name of User:	*William Bellinazo Roca*
Assessment completed by:	*William Bellinazo Roca*
Assessment checked by:	*Aristides Kiprakis*
Date of Assessment:	*24/03/2017*
Any further action needed? Yes / No Please specify action required.	*No*
Follow up action completed on:	

Assessment Checklist

Risk Factors	Yes / No		Things to Consider	Action to take
1. DISPLAY SCREENS				
Are the characters clear and readable?	Y		Make sure the screen is clean and cleaning materials are made available. Check that text and background colours work well together.	
Is the text size comfortable to read?	Y		Software settings may need adjusting to change text size.	
Is the image stable, i.e. free of flicker?	Y		Try using difference screen colours to reduce flicker, e.g. darker background and lighter text, increase refresh rate of monitor setting. If problem persists, contact your IT support.	
Is the screen's specification suitable for it's intended use?	Y		For example, intensive graphic work or work requiring fine attention to small details may require large display screens.	

Are the brightness and /or contrast adjustable?	Y		Separate adjustment controls are not essential, provided the user can read the screen easily at all times.	
Does the screen swivel and tilt?	Y		Swivel and tilt need not be built in; you can add a swivel and tilt mechanism. However, you may need to replace the screen if: - Swivel/tilt is absent or unsatisfactory - Work is intensive; and/or -The user has problems getting the screen to a comfortable position. The height of the screen should be roughly at eye level. A monitor stand may be required. If using an LCD screen, ensure it is adjustable in height, alternatively use a monitor stand.	
Is the screen free from glare and reflections?	Y		Find the source of the reflections. You might need to move the screen or even the desk and/or shield the screen from the source of the reflections. Screens that use dark characters on a light background are less prone to glare and reflections.	
Is the user facing the screen.	Y		Position the screen in front of the user, to avoid any twisting.	
Are adjustable window coverings provided and in adequate condition?	Y		Check that curtains/blinds are in good working order. If not, report to Estates and Buildings. If these measures do not work, consider anti-glare screen filters as a last resort and seek specialist help.	
2. KEYBOARDS				
Is the keyboard separate from the screen?	Y		This is a requirement, unless the task makes it impracticable (e.g. where there is a need to use a portable computer).	
Does the keyboard tilt?	Y		Tilt need not be built in	

Is it possible to find a comfortable keying position?  YES NO  NO	Y		Try pushing the display screen further back to create more room for the keyboard, hands and wrists. Keep elbows close to the body, do not overstretch the arms. Users of thick, raised keyboards may need a wrist rest. Users may find the use of a compact mini-keyboard more comfortable.	
Does the user have good keyboard technique?	Y		Training can be used to prevent: - hands bent up at wrist - hitting the keys too hard - overstretching the fingers	
Are the characters on the keys easily readable?	Y		Keyboards should be kept clean. If characters still cannot be read, the keyboard may need modifying or replacing. Use a keyboard with a matt finish to reduce glare and/or reflection.	
3. MOUSE, TRACKBALL, ETC				
Is the device suitable for the tasks it is used for?	Y		If the user is having problems, try a different device. The mouse and trackball are general-purpose devices suitable for many tasks, and available in a variety of shapes and sizes. Alternative devices such as touch screens may be better for some tasks (but can be worse for others). Check the device has been set to suit the user (for right or left hand user).	

Is the device positioned close to the user?  NO  YES  YES	Y		Most devices are best placed as close as possible e.g. right beside the keyboard. Training my be needed to: -prevent arm overreaching -tell users not to leave their hand on the device when it is not being used - encourage a relaxed arm and straight wrist. A compact keyboard will help the user to avoid overreaching.	
Is there support for the device user's wrist and forearm?	Y		Support can be gained from, for example, the desk surface. If not, a separate supporting device (gel filled) may help. The user should be able to find a comfortable working position with the device.	
Does the device work smoothly at a speed that suits the user?	Y		Check if cleaning is required (e.g. of mouse ball and rollers). Check the work surface is suitable. A mouse mat may be needed.	
Can the user easily adjust software settings for speed and accuracy of pointer?	Y		Users may need training in how to adjust device settings.	
4. SOFTWARE				

Is the software suitable for the task?	Y		Software should help the user carry out the task, minimise stress and be user-friendly. Check users have had appropriate training in using the software. Software should respond quickly and clearly to user input, with adequate feedback, such as clear messages.	
5. FURNITURE				
Is the work surface large enough for all the necessary equipment, papers etc?		N	Create more room by moving printer, reference materials etc elsewhere. Use multilevel trays for papers/documents. If necessary, consider providing new power and telecom sockets, so equipment can be moved. There should be some scope for flexible rearrangement.	Moved some old papers to adequate study area in my room.
Can the user comfortably reach all the equipment and papers they need to use?	Y		Rearrange equipment, papers etc to bring frequently used things within easy reach. A document holder may be needed, positioned to minimise uncomfortable head and eye movements.	
Are the surfaces free from glare and reflection?	Y		Consider mats or blotters to reduce reflections or glare.	

Is the chair stable & suitable for the user? Does the chair have a working: - seat back height and tilt adjustment? - Seat height adjustment? - Swivel mechanism? - Castors or glides?	Y		The chair may need repairing or replacing if the user is uncomfortable, or the adjustment mechanisms are faulty. Contact the University Furniture Office.	
Is the chair adjusted correctly?	Y		The user must be familiar with the chair adjustments. Adjust the chair height to sit with elbows at approx. 90º & 2cm above the desk when touching the G & H keys. The user should be able to carry out their work sitting comfortably. Consider training the user in how to adopt suitable postures while working. The arms of chairs can stop the user getting close enough to use the equipment comfortably. Consider chairs without armrests or alternatively, adjustable armrests. Move any obstructions from under the desk.	
Is the lower back supported by the chair's backrest?	Y		The user should have a straight back, supported at all times by the chair, with relaxed shoulders.	

Are forearms horizontal and eyes at roughly the same height as the top of the screen?	Y		Adjust the chair height to get the user's arms in the right position; adjust the monitor height/tilt if necessary.	
6. ENVIRONMENT				
Is there enough room to change position and vary movement?	Y		Space is needed to move, stretch and fidget. Consider reorganising the office layout and check for obstructions. Cables should be tidy and not a trip or snag hazard.	
Is the lighting suitable, e.g. not too bright or too dim to work comfortably?	Y		Users should be able to control light levels, e.g. by adjusting window blinds or light switches. Consider shading or repositioning light sources or providing local lighting, e.g. desk lamps (but make sure lights don't cause glare by reflecting off walls or other surfaces).	
Does the air feel comfortable?	Y		VDUs and other equipment may dry the air. Green plants may help to increase moisture levels in the air. Circulate fresh air if possible. As a last resort, if discomfort is severe, consider a humidifier.	
Are levels of heat comfortable?	Y		Can heating be better controlled? More ventilation or air-conditioning may be required if there is a lot of electronic equipment in the room. Or, can users be moved away from the heat source?	
Are levels of noise comfortable?		N	Consider moving sources of noise, e.g. printers, away from the user. If not, consider soundproofing.	Walls in my accommodation do NOT provide adequate acoustic insulation. Will work on library in case of prolonged noises.
7. ELECTRICAL				

Have you carried out a user check (visual inspection) of the visually accessible parts of the equipment and it's cable, plug and extension cable.	Y		See http://www.docs.csg.ed.ac.uk/Safety/Policy/Part3.pdf for more information on user checks. Carry out a user check when the equipment has been relocated. Any faults or significant wear and tear, must be reported and repaired as soon as possible (contact your local computing support) Do not use any equipment if defective. Remove from operation and label 'DO NOT USE - EQUIPMENT FAULTY'.	

Final Questions to Users:

- Is a portable computer being frequently used? If so, reduce its use to a minimum. Alternatively, have a docking station (separate keyboard, separate screen or screen elevated, separate mouse or tracking device). More detailed guidance on working with laptop computers is available at http://www.docs.csg.ed.ac.uk/Safety/health/DSE.pdf.

Yes, I will wok mostly on my personal notebook for convenience. Will try to go to the library to vary from time to time.

- Has the checklist covered all the problems the user may have working with the DSE?

For now, yes. If any other risk factors arise I will contact my supervisor.

- Has the user been advised of their entitlement to eye and eyesight testing, and advised to contact the Occupational Health Unit or the Health and Safety Office to arrange appropriate eye sight testing?

Yes, I already had an eye sight testing appointment. The doctor said he doesn't recommend me glasses as it is not a problem for me at the moment.

- Does the user take regular breaks working away from the DSE?

Yes, naturally. Whenever I feel like I need a break, usually every 1h~2h.

- Has the user read the leaflet "Are you keying comfortably"?

Yes, read it and downloaded it in case of need for future reference.